Concept of Intelligent Mechanical Design for Autonomous Mobile Robots

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Abstract

During the 21st century, it is expected that the robots with different degrees of autonomy and mobility will play an increasingly important role in all side of human life. Thus these kinds of robots will become much more complex than today, and the development of such robots present a great challenge for researchers. However, drawbacks of robot complexity, necessity of more complex hardware, software and mechanical structure may lead to low reliability and increasing of size, weight, cost, power consumption and motion limitation. In order to avoid the problems mentioned above, the simplification of robots mechatronics will be a critical point in their design.

In this thesis, the concept of "Intelligent Mechanical Design" will be presented and how a mechanical structure can be designed to have an effect to the robot controllability, simplification and its tasks performance is discussed. The description of this concept will lead us to establish the landmarks of the territory of mechanical designing in the form of seven design principles. The design principles, named "Mecha-telligence principles", provide a guidance on how to design autonomous mobile robots mechanics. These principles guide us in asking the right questions when investigating issues concerning a self-controllable, reliable, realizable, and compatible mechanics for autonomous mobile robots.

To show how the "Mcaha-telligence principles" can be applied on the processes of the design of robots mechanics, we proposed a novel methodology, named "Mecha-telligence methodology". Mechanical design in the proposed methodology is performed based on preference of classification of the robot specification described by interaction of the robot with its environment and, also, the physical parameters of the robot mechatronics itself. In this approach the robot specification is classified to a set of high-level- and low-level-specification which can be expressed as tasks and physical parameters of the robot, respectively. A main goal in these analyzing process of the robot specification, is that, figuring out to a Mono-spec layer (the last layer of low-level-specification) including a simple basic function or selecting a sensor for a single task or behavior. The process of mechanical design will be started based on an important defined robot mono-spec, and then will be proceeded to realize the other mono-specs

by adding the minimum actuator(s) and sensor(s). In each step of the mechanical design in this methodology, the proper and sufficient mechanics will be achieved by considering the robot tasks, behaviors, morphology, and by applying the description of environmental and physical-morphological constraints on the design process.

To prove the validity of the proposed method we concentrate on developing of the mechanical structures and devices of three types of autonomous mobile robots used in the three different educational, entertainment and industrial applications. The first project is on developing an autonomous mobile soccer robot, “Musashi robot”, which has a fully mechatronics modular architecture including a strong ball-kicking device with capability of lifting a ball and a ball-holding mechanism, aiming at getting champion in RoboCup Midsize League. The second challenge is on the design, modeling, simulation and implementation of a series of entertainment robots, named "Jumping Joe"s, with capabilities of the fast waking up, jumping, and somersault actions, exhibited in Aichi Exposition 2005. In third project we propose a new approach to the sewer pipe inspection by developing a fully autonomous mobile robot “KANTARO”. Cooperation in this national funding project, is our third challenge item in mechanical design to compromise how a passive-active intelligent moving mechanism can be employed as a robot platform for inspecting the real sewer pipe network. In these three projects we describe, not only, the mechanical design process based on “mechatelligence design” methodology, but also, the detail design which is considered to lead readers to get familiar as much as possible to our vision relative to the presented design methodology.

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Introduction

1.1 Objectives

Early development of robotics research in the 1960s and 1970s was focused on industrial robots/manipulators for the automation of industrial processes. Mechanical manipulators resemble human arms are deployed in the factories for various automation tasks. In the 1980s, robots started walking out of the manufacturing floors in the form of wheeled or legged mobile mechatronic systems and underwater autonomous vehicles. The roles of robots are no longer limited to automated factory workers but are changing into explorers for hazardous, human-unfriendly, and extreme environments, and servants to provide surveillance, security, and cleaning tasks. Ingenious autonomous robotic systems that equipped with artificial intelligence capability resemble biological counterparts were emerging in the late 1990s, such as Sonys Aibo robotic dog, and Hondas humanoid robots from P2, P3, to Asimo. These systems not only walked out of factories and service sector but also walked into our everyday life and households. Eventually these robots are going to co-habit with humans to provide assistance and cares.

Thereby, it is expected that the robots with different degrees of autonomy and mobility will play an increasingly important role in all side of human life, thus these kinds of robots will become much more complex than today, and the development of such robots presents a great challenge for researchers. However, drawbacks of robot complexity, necessity of more complex hardware, software and mechanical structure may lead to low reliability and increasing of size, weight, cost, power consumption and motion limitation. In order to avoid the mentioned problems, the simplification of robots mechatronics will be a critical point in their design. Although every working in robotics soon confronts the reality that the design of the mechanical structure greatly affects its performance and controllability, the theoretical and practical investigations of the relationship (between the robot mechanical structure and its resulting controllability and reliability) have largely been ignored. This is not simply a peripheral oversight, but a fundamental gap in field of robotics.

The main question to be answered in this context is: "what is the unified approach or methodology to actually design a proper mechanics for autonomous mobile robots to provide a high degree of performance, functionality, simplicity and reliability". In this direction, there is no concrete method or approach to actually design a system, in so much as there does not exist a unified approach to creativity. Given a particular need, each individual designer would probably design something different[1]. In this thesis the concept of "intelligent mechanical design" will be presented. The definition of this concept will lead us to provide a design methodology, called "Mecha-telligence methodology", for design of autonomous mobile robots mechanics. In this methodology the proper and sufficient mechanics will be achieved by considering the robot tasks, behaviors, morphology, and applying the description of environmental and physical-morphological constraints on the design process. To prove the validity of proposed method we concentrate on developing of the mechanical structure and devices of three types of autonomous mobile robots used in the three different educational, entertainment and industrial applications. In these three projects we describe, not only, the mechanical design process based on "mecha-telligence design" method, also, the detail design which is considered to lead readers to get familiar as much as possible to our vision relative to the presented design methodology.

1.2 Overview of the Thesis

In "chapter 2: Mechanics & Intelligence" the concept of "intelligent mechanical design" will be presented to realize how a mechanical structure can be designed to have an effect to the robot controllability, simplification and its tasks performance. The description of this concept will lead us to establish the landmarks of the territory of mechanical designing in the form of seven design principles. The design principles, named "Mecha-telligence principles", provide a guidance on how to design autonomous mobile robots mechanics. These principles guide us in asking the right questions when investigating issues concerning a self-controllable, reliable, realizable, and compatible mechanics for autonomous mobile robots. To show how the "Mecha-telligence principles" can be applied on the processes of the design of robots mechanics, we proposed a novel methodology, named "Mecha-telligence methodology". Mechanical design in the proposed methodology is performed based on preference of classification of the robot specification described by interaction of the robot with its environment and, also, the physical parameters of the robot mechatronics itself. In this approach the robot specification is classified to a set of high-level- and low-level-specifications which can be expressed as tasks and physical parameters of the robot, respectively. The high-level-specification, including the two layers, are described by considering the robot tasks and its interaction with the environment where it is used. A low-level-specification may, consecutively, consists of a set of layers describing the physical setup of the robot, its body, sensory, and motor systems. A main goal in these analyzing process of the robot specification, is that, figuring out to a Mono-spec layer (the last layer of low-level-specification) including a simple basic function or selecting a sensor for a single task or behavior.

In "Mecha-telligence design" methodology the mechanical design will be started based on an important defined robot mono-spec, and it will be extended to realize the other mono-specs by adding the minimum actuators and sensors to the design. In each step of the design process, also, we are trying to come up to the proper solution by considering the robot morphology, design the suitable actuators and employing passive mechanisms which have inherent intelligence characteristics. To prove the validity of proposed method we concentrate on developing of the mechanical structure and devices of three types of mobile robots used in the three different educational, entertainment and industrial applications.

"Chapter 3: Soccer robot" is our first mechanical design challenge on developing an autonomous mobile soccer robot which has a fully mechatronics modular architecture including a strong ball-kicking device with capability of lifting the ball and a ball-holding mechanism, aiming at getting champion in RoboCup Midsize League. We proposed a mechatronics modular platform which consists of an omni-directional moving mechanism, an omni-vision and a novel ball-kicking-lifting-holding device. In this approach we show that selecting a proper mechanical moving mechanism and a suitable vision system can lead to realize a reliable, simple, and low cost robot comparing with the first version of our car-like soccer robot which includes many different kinds of sensors and a complex design structure. The main focus in this theses, with regard to this project, is on detail design and developing process of a strong kicking device with capability of shooting (up to 5 [m/s]), lifting (up to 120 [cm]), and holding the ball. The ball-kicking is accomplished by design of an unique spring charging mechanism called "Cam Charger". The key idea is to charge a series of strong torsion springs by using a cam with special shape. One of the specific features of the Cam Charger mechanism is that charging, keeping and releasing of the springs energy are done only by employing a simple DC motor-gearhead and a limit switch. Another special point is that the design of the kicking mechanism can be extended to hold the ball by adding a simple linkage mechanism to the Cam Charger structure. The same motor and the limit switch, used for the ball-kicking, can be employed to activate and control the linkage mechanism of ball-holding. This kicking device, also, has an inherent design characteristic to lift the ball by using the different shape of plates installed on the kicker.

Next chapter "chapter 4: Artistic Robot" is our second challenge on the design, modeling, simulation and implementation of a series of entertainment robots named "Jumping Joe", exhibited in Aichi Exposition 2005. Jumping Joe robots, artistic and agile robots, can perform several rapid movements such as fast wake up, jumping and somersault. In order to realize acrobatic movements, four different actuators which can create the high-speed movements are developed: Inertia Actuator, Hip joint, Knee joint and Cam Charger. Inertia Actuator consists of a H-shape cylindrical rotor , a DC motor, and a brake mechanism, is an inertial energy-storage device. Inertia Actuator absorbs mechanical energy by increasing its rotor angular velocity and delivers energy by decreasing its rotor velocity. Inertia Actuator can generate a small internal torque by changing the speed of the rotor and a big internal torque in short time by using a brake to stop the high speed rotor in a moment. Hip joint and knee joint are designed based on a parallel and Lever-Crank mechanisms, respectively. Parallel mechanism is utilized, because the output torque of this kind of mechanisms can be increased without a large ratio gear so that, a speedy and powerful motion can be expected. In order to realize the jumping capability, "Cam Charger" mechanism presented as a kicking device for RoboCup is redesigned to fit to the foot shape. In this case we designed a unique and compact cam including a releasing part to avoid the distribution of the force at the moment of springs energy releasing to the foot structure. To achieve the reliability and easy to assemble and maintenance features, "Jumping Joe"s are designed to have a modular architecture in their mechanical parts and eclectic circuits. "Jumping Joe"s are made of combination of four main modules: Upper body, Hip joint, Knee joint and Jumping foot. By using the modular architecture for "Jumping Joe"s, we can realize the different kinds of artistic robots, only, by plugging the different modules to each other.

"Chapter 5: Sewer Pipe Inspection Robot" will describe a new approach to the sewer pipe inspection by developing a fully autonomous mobile robot "KANTARO". Cooperation in this national funding project, is our third challenge item in mechanical design to show how a passive-active intelligent moving mechanism can be employed as a robot platform for inspecting the real sewer pipe network. With regard to the current sewer pipe inspection technology, all commercial robots are completely tele-operated, usually via a tether cable, by a human operator. In addition, current sewer inspection robots have a poor mobility function to pass any kind of pipe-bends such as curves and junctions so that those robots are only capable to move into the straight pipes. Inspecting the sewage pipes using the state of the arts inspection methods by the current robots is costly, mostly human cost, and not fast enough to check and inspect the amount of sewage pipes will grow stronger than it has actually happened, specially in Japan. In this part of thesis we propose an innovative, fast and robust sewer inspection method by using a passive-active intelligent, fully autonomous, un-tethered robot called KANTARO which fits to the pipes within a diameter range of 200-300 millimeters. KANTARO prototype robot, including a novel passive-active intelligent moving mechanism (the main focus in this theses, with regard to this project), can move into the straight pipe and pass different kinds of pipe bends without need to any intelligence of the controller or sensor reading. In order to realize a fully autonomous inspection robot, we also developed a small and intelligent 2D laser scanner for detecting of the navigational landmarks such as manholes and pipe joints independently with main computer system, and fusion with a fish eye camera to assist the pipe state and fault detection. Consequently, we propose a fully autonomous sewer inspection system but with a possibility to interfere the KANTARO control as it drives through the pipe either via an optical underground wireless communication module, developed in this project, or via a life-optic-untethered cable.

Chapter 2
Mechanics & Intelligence

Chapter 2

Mechanics & Intelligence

2.1 Introduction

One of the basic, fundamental, and significant question in the field of mechanics related to design an autonomous mobile robot is that:

"What is the *ideal* mechanical design for an *autonomous mobile* robot which can perform the defined *desired behavior*(s) in an *environment* in which it will be used?".

By thinking deeply about this basic question and trying to disintegrate it in detail, we can realize two main objections: first, the exact meaning of the term of "ideal" regard to the amount of terms (such as Reliable, Optimal, Robust, Simple, proper, and etc.) that can be replaced to it and second, difficulties and lack of exact definition and description of these terms related to design a mechanic of an autonomous mobile robot (see Fig. 2.1). In this thesis we figure out the mentioned problems by proposing to integrate all possible terms at one, which is called "Intelligent mechanical design" (Fig. 2.2). Note that the meaning of "Intelligent mechanical design", presented in this thesis, is not same as definition of the common phrases such as "Intelligent design",

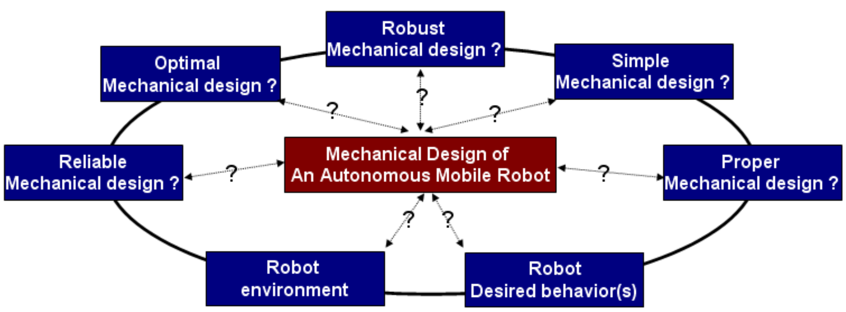


Figure 2.1: Mechanical design of an autonomous mobile robot and related factors.

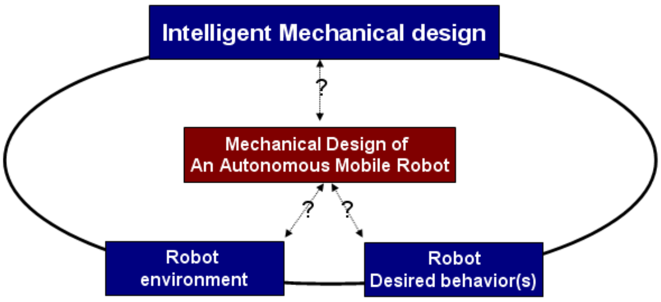


Figure 2.2: New approach to mechanical design of an autonomous mobile robot and related factors.

"Intelligent mechanics", "Mechanical intelligence", and "Intelligent designer". In fact, as it will be described in this chapter, "Intelligent mechanical design" is a primary concept for realization of a methodology applying for mechanical design of autonomous mobile robots. Using this methodology, called "Mecha-telligence methodology", can lead the designer to create and design the simple, proper and sufficient mechanical solution for complex problem. Output of a mechanical design based on proposed methodology may include intelligent mechanics, passive mechanism, mechanics related to body morphology and materials and also mechanical solution exploited by the robot interaction with its environment. Since "Mecha-telligence methodology" can be recognized as a guidance method, the results of design ,also, can be affected by the designer expertness and his/her intelligence and punctilious. For all of these, we selected the word of "Intelligent" as a first step of our approach in realization of a methodology to design the ideal mechanics for robots with the different degrees of autonomy and mobility.

Using this methodology is not only for autonomous mobile robots, also can be extended and applied for any kinds of systems which request mechanical structures. In this thesis we focus on mechanical developing process of autonomous mobile robots, because we believe that these types of robots will play an increasingly important role in all side of human life and the development of such autonomous robots presents a great challenge for researchers. In this direction, exact understanding of definition of "Intelligence" (subsection 2.2.1), "Autonomous robot", "Mobile robot", "task and desired behavior" (subsection 2.2.2), and "Robot environment" are key points to describe the concept of "Intelligent mechanical design" and also the definition and implementation of "Mecha-telligence methodology".

2.2 What is Intelligence?

"Intelligence is a large field and the human being is not yet ready to even understand its fundamentals. Maybe he will never ever understand what it's all about. We are living in a huge complex environment and nature is just too complex to explain in three to four sentences. Intelligence is something that was created by nature and for sure not by us humans ourselves"[2]. There are the attempts of many leading experts in the field to describe intelligence. The results were all kind of different definitions none of those experts seemed to be sure about their own definition. One of the wonderful approach, not only, describe the meaning of "intelligence", also use this item to show the design process of an autonomous agent is that a book with the title "UNDERSTANDING INTELLIGENCE" written by Rolf Pfeifer and Christian Scheier. Here we will briefly present a summery of their approach[1]. In the next subsection, we figure out, not only, meaning of the term of "Intelligence, but also consideration of the definitions of the other necessary terms related to description of "Intelligence", presented in this book, in detail. Because complete understanding about their approach to describe the term of "intelligence" and also design process of autonomous agents can lead us to explain, our concept of "Intelligent Mechanical Design" for autonomous mobile robots presented in this thesis in proper and easy way, Some important terms are described in the next sections.

2.2.1 Definitions of The Necessary Selected Terms

Agent

"The term is used in many ways. (1) As an umbrella term if no distinction between humans, animals, and robots is intended. (2) To designate an animated creature in cyberspace. (3) To distinguish a certain type of simulation model (agent simulation) from others. In agent simulations, agent and environment are modeled separately and have independent dynamics. Agents acquire information about the environment only through their (simulated) sensory systems. (4) In the context of Internet, to describe the programs (software agents) that perform a certain service for a user, typically information retrieval."

Intelligence

"No generally accepted definition exists. The term is used to describe *complete agents* (agents that are autonomous, self-sufficient, embodied, and situated) that resolve the *diversity-compliance trade-off* in interesting way. Intelligence must always be seen with respect to *a particular ecological niche*." Figure 2.3 and 2.4 show two sample of a complete agent, Todas Fungus Eater and a garbage-collecting robot.

"Todas Fungus Eater is operating on a distant planet. its task is to collect uranium

[1] Most of the materials presented in this section (2.2) have been selected from "UNDERSTANDING INTELLIGENCE" book.[3] The sentences placed in "this symbol" are selected material.

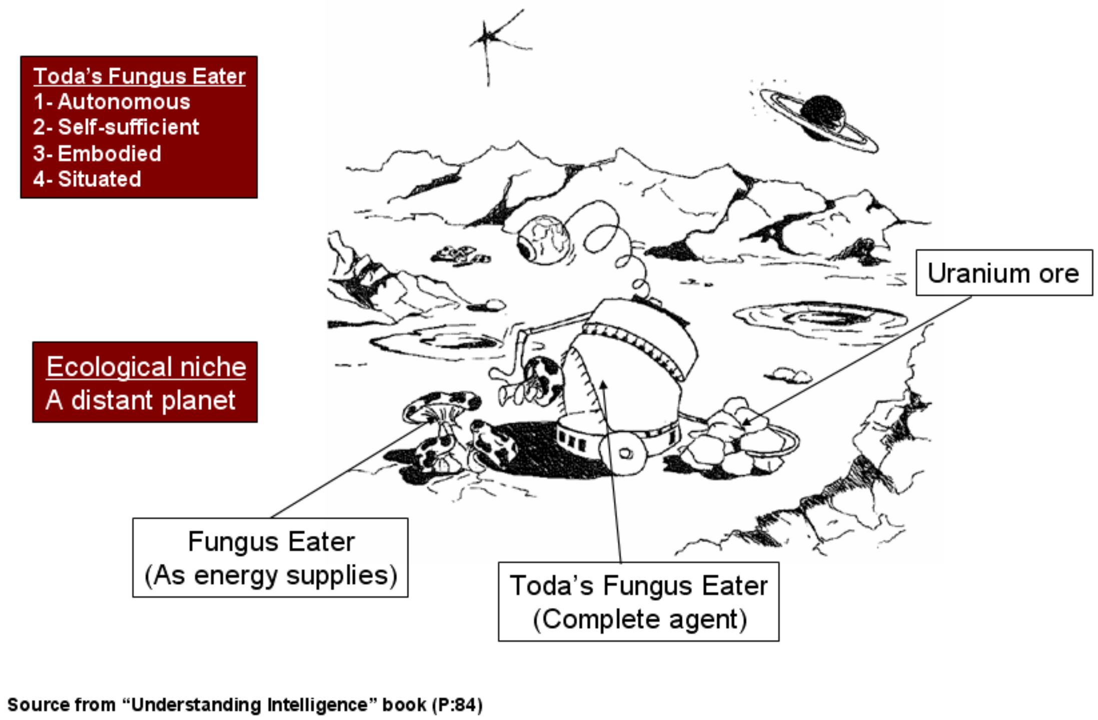


Figure 2.3: A sample of a complete agent, Garbage robot.

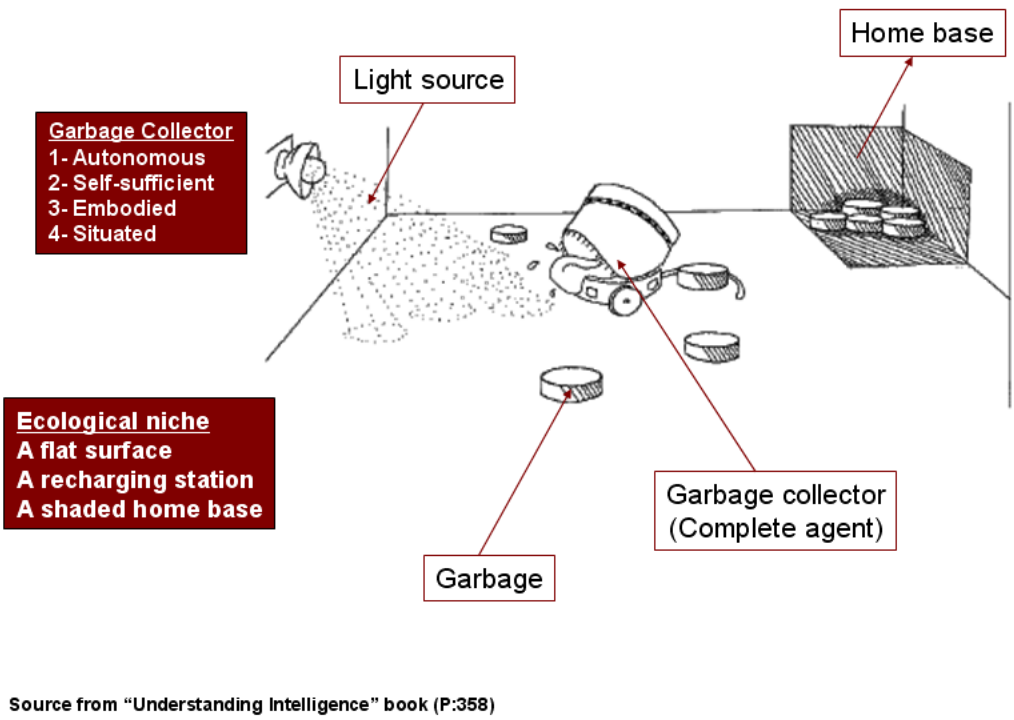


Figure 2.4: A sample of a complete agent, Garbage robot.

ore. It feeds on a certain type of fungs. It is autonomous (too far away for remove control), self sufficient (it must take care of its own energy supply which, in this case, is a particular type of funguse that grows on this planet, thus the name Fungus Eater), embodied (it exist as a physical system), and situated (its knowledge about the environment is acquired through its own sensory system). In the Fig. 2.3, it is in the process of devouring fungus.

"The task of the garbage-collecting robot is to collect the objects in its environment and bring them to the home base. At the same time, it has to sustain itself by regularly visiting the charging station, which is equipped with a light source. The robot uses this light to find the charging station and the home base with its ambient light sensors, that is, by performing phototaxis (i.e., moving toward a light source) and antiphototaxis (moving away from the light source), respectively".

Autonomous Agent

"An agent that has a certain independence of external control."

Self-sufficient Agent

"An agent is said self sufficient if it is cable of sustaining itself over extended periods of time."

Embodiment/Embodied Agent

"A term used to refer to the fact that intelligence can not merely exist in the form of an abstract algorithm but requires a physical instantiation, a body. In artificial systems, the term refers to the fact that a particular agent is realized as a physical robot or as a simulated agent. Embodied agents must be realized as physical systems capable of acting in the real world."

Situated Agent

"An agent is said to be situated if it acquires information about its environment solely through its sensors in interaction with the environment. A situated agent interacts with the world on its own, without an intervening human. It has the potential to acquire its own history, if equipped with appropriate learning mechanisms."

Diversity-compliance Trade-off

"Generating of diversity while complying with the givens of the system. Represents a compromise between, on the one hand, generating new behavior, and on the other, conforming to existing conditions."

Ecological Niche

"The ecological niche for an animal is the range in each variable in its environment, such as temperature, humidity, and food items, within which a species can exist and reproduce. Niche occupancy usually implies competition (when animals of different species use the same resources)."

Behavior

"What an autonomous agent is observed doing. Always the result of an interaction of an agent with its environment."

Task

"As used in a design context, the designer's perspective on what the agent should accomplish. A task is accomplished by a set of behaviors."

2.2.2 Definition of Task and Desired Behaviors

In this subsection we distinguished between tasks and desired behaviors. "Both robots in Fig. 2.5 achieve the task of collecting the ping pong balls, but they do so using behaviors that are very different. So the task is consented with the effect of behaviors rather than the behaviors themselves. Often the separation is not so clear." For example mowing robot. "The robot's task is to mow the lawn. Mowing is in fact the desired behavior to achieve the task of keeping the grass short. A garbage-collecting robot obviously has the task of collecting garbage, or rather of eliminating garbage from the streets. Its designer has to map this task onto desired behaviors like searching for garbage, picking it up, bringing it back to garbage truck, ad so forth. Alternatively the garbage could be burned on the spot, requiring no collecting. Note that, strictly speaking, the definition of the task is independent of the *robot* itself. The designer

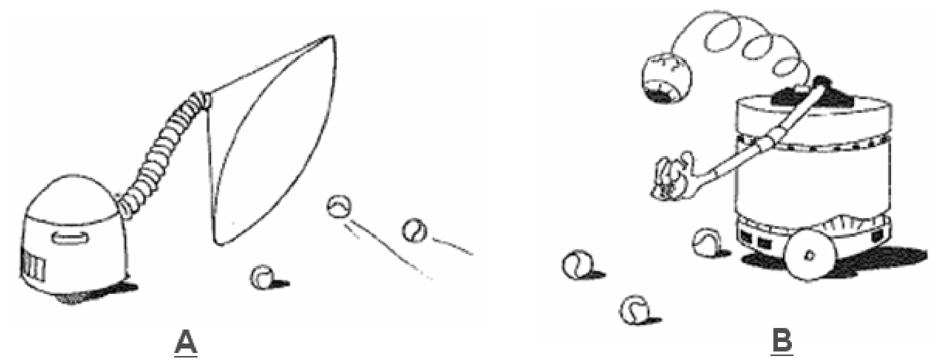


Figure 2.5: Ping pong collecting robot (printed from [3] (P:301))

decides what the tasks of the *robot* are to be and designs the *robot* in such a way that it can accomplished them. This does not mean that there must be an explicit representation of the task within the *robot*.[2]"

2.2.3 Design principles for autonomous agents

Figure 2.6 shows Rolf Pfeifer and Christian Scheier's approach to establish the landmarks of the territory of designing an autonomous agent in the form of eight design principles. "The set of design principles consists of two parts: a meta principle (prin-

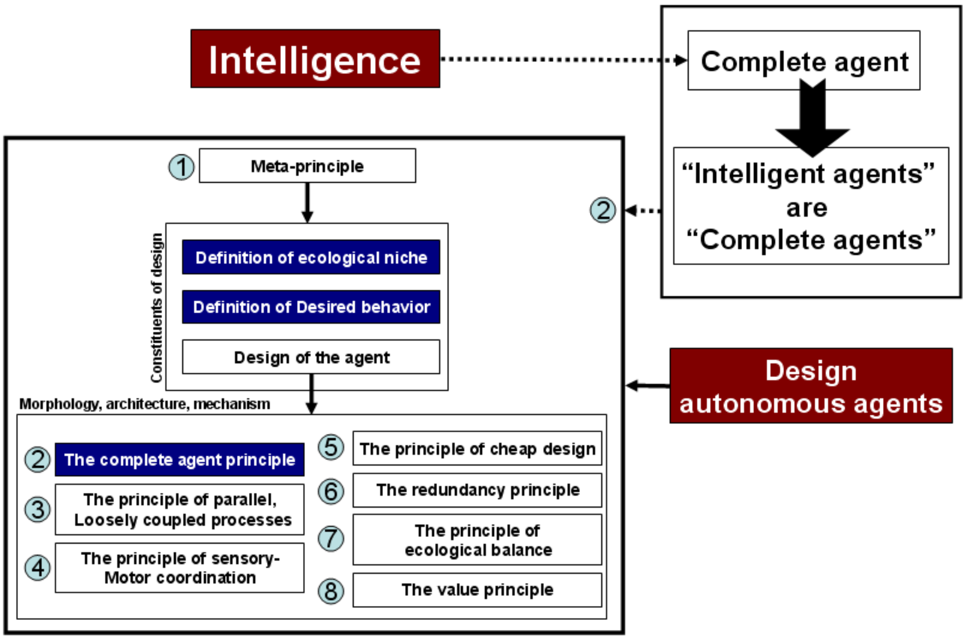


Figure 2.6: Overview of design principles for autonomous agents [3] (P:303).

ciple 1) that tells us the essential constituents of the design process, and a number of principles that concern the agent itself, its morphology, its sensors and effectors, and its control architecture, that is, its internal mechanisms (Principles 2 to 8)". The definition of robot environment and robot behaviors and tasks are highlight as a meta principle to show the significant effect of these terms in the design process of an autonomous agent. Also, note that using the term of "Intelligence" for describing a *complete agent*, is landmark as second principle. we refer the readers, in case of interested, about more detail of the principles to "UNDERSTANDING INTELLIGENCE" book, chapter 10.

[2] The terms of *robot*, typed in format of Italic in the two last sentences, in original reference are "Agent" that they are changed to the term of "Robot" regards to our concept in this thesis.

2.3 Intelligent Mechanical Design

In this thesis the concept of "Intelligent mechanical design" is presented to show how a mechanical structure can be designed to have an effect to the robot controllability, simplification and its tasks performance. The description of this concept will lead us to establish the landmarks of the territory of mechanical designing in the form of seven design principles. The same as Rolf Pfeifer approach in describing the term of "intelligence" we will try to come up to an accepted definition about "Intelligent mechanical design" and consecutively, we will describe the necessary terms related to the definition of the presented concept.

Intelligent mechanical design

The term can be used to describe *complete mechanical designs* (*designs that are self-controllable, reliable, realizable, and compatible*) that resolve *the functionality-usability trade-off* in optimal way. Mechanical design must always be considered with respect to a particular *environmental niche*.

Self-controllable

A mechanical design is self-controllable, if it can be controlled by a set of certain internal hardware, independence of external motive forces. Self-controllability must always be considered with respect to a specific system.

Reliable

A mechanical design is reliable, if the mechanical design parameters specification can be realized during requested system life-time. In this approach the number of actuators and sensors used for a system with certain desired tasks can be recognized as a remarkable mechanical design parameter that it has direct affect to the system reliability.

Realizable

A mechanical design is realizable, if it can be realized as a real mechanical structure using the current manufacturing methods and the commercial materials exist in the market. Realizable mechanical design can be affected by a number of user requests such as cost, size, weight, water proof, dust proof, etc.

Compatible

A mechanical design is compatible, if the design of the sensory-motor architecture has compatibility with the size, weight and shape of the hardware. Compatibility must always be considered with respect to a specific system.

The functionality-usability trade-off

Represents a compromise between, on the one hand, adding new functionality, and on the other, preserving usability condition [4].

Environmental niche

Environmental niche for a robot is described by the range in each variable in its ***environment***, within which a mechanical design as a part of a system should be realized. We used the term of "environment" here to mean essentially two things. First, the direct-physical meaning defined by the area in which the robot is used, including the natural or artificial objects. Second, the indirect-physical meaning expressed by the possible existing rules or user requested in case of considering the robot usability. This requires some explanation that we explain here in form of examples. let's call the example of garbage-collecting robot which we introduced earlier in this chapter. Figures 2.7 to 2.10 show four examples of garbage-collecting robot different in the description of environmental niche and related constraints. In the first example, Fig. 2.7, robot should collect the garbage in the corner of the room. The environmental niche and constraints can be defined as follows:
Environmental niche:

- A flat surface (Direct-physical meaning)
- Indoor environment (Direct-physical meaning)

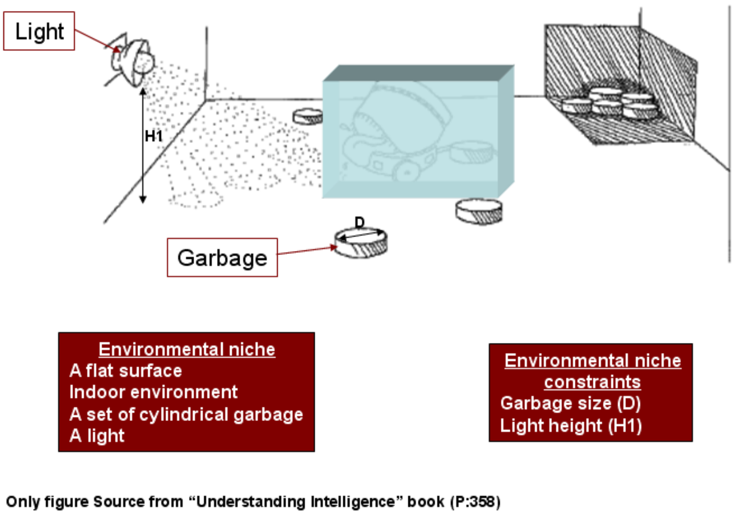


Figure 2.7: First example of garbage-collector robot.

- A set of cylindrical garbage (Direct-physical meaning)
- A light (Direct-physical meaning)

Environmental niche constraint:

- Garbage size (D) (Direct-physical meaning)
- Light height (H1) (Direct-physical meaning)

In the second example, compare with the first example, a garbage room is located in a corner of the room (Fig. 2.8). Also the limitation cost for making the robot in this example has been assumed. By changing the environment of the robot, a garbage room and the cost limitation, the environmental niche and relative constraints will be changed as follows:
Environmental niche:

- A flat surface (Direct-physical meaning)
- Indoor environment (Direct-physical meaning)
- A set of cylindrical garbage (Direct-physical meaning)
- A light (Direct-physical meaning)
- A garbage room (Direct-physical meaning)
- Cost limitation (it may be considered as a user request) (Indirect-physical meaning)

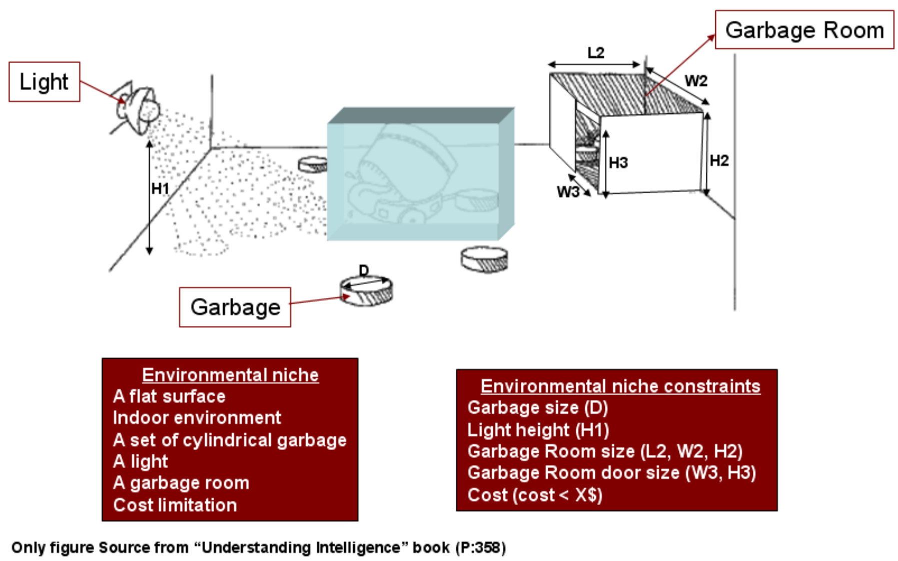


Figure 2.8: Second example of garbage-collector robot. Cost limitation is assumed.

Environmental niche constraint:

- Garbage size (D) (Direct-physical meaning)
- Light height (H1) (Direct-physical meaning)
- Garbage room size (L2, W2, H2) (Direct-physical meaning)
- Garbage room door size (W3, H3) (Direct-physical meaning)
- Cost (cost < X $) (Indirect-physical meaning)

In this example "cost limitation" illustrates the second aspect of environmental niche and relative constraint meaning, presented in this thesis. Third example indicates the second aspect of environmental niche in form of game rules (Fig. 2.9). we assumed that the robot will be designed based on the rules to participate in garbage-collecting competition. With regard to the rules, there are limitations in size of the robot so that the robot should be fit in a box with specific dimensions. In this case, the environmental niche and relative constraint can be itemized as follows:
Environmental niche:

- A flat surface (Direct-physical meaning)
- Indoor environment (Direct-physical meaning)
- A set of cylindrical garbage (Direct-physical meaning)
- A light (Direct-physical meaning)

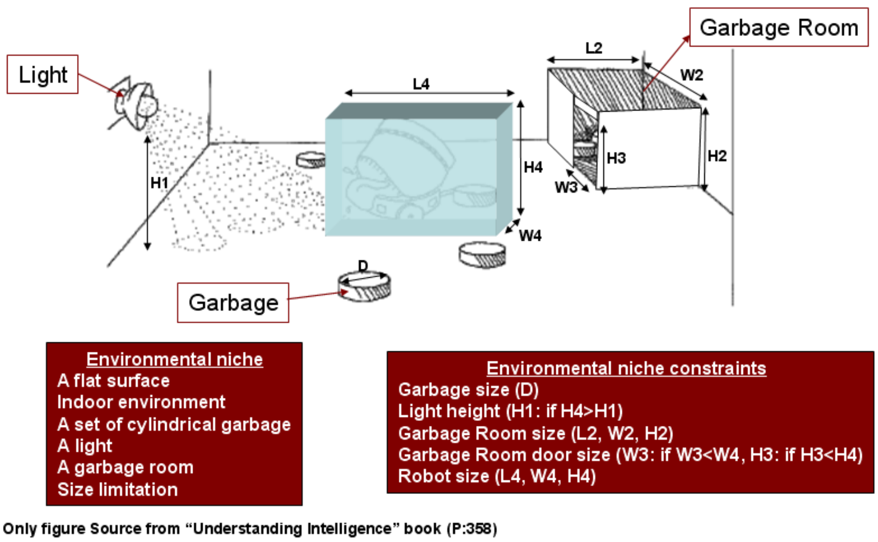


Figure 2.9: Third example of garbage-collector robot. Size limitation is assumed.

- A garbage room (Direct-physical meaning)
- Size limitation (it is considered based on the game rules) (Indirect-physical meaning)

Environmental niche constraint:

- Garbage size (D) (Direct-physical meaning)
- Light height (H1: if H4>H1) (Direct-physical meaning)
- Garbage room size (L2, W2, H2) (Direct-physical meaning)
- Garbage room door size (W3: if W3<W4, H3: if H3<H4) (Direct-physical meaning)
- Robot size (L4, W4, H4) (Indirect-physical meaning)

Note, because of the robot size limitation, some environmental niche constraint should be considered in form of conditional constraints. As an example, the height of the light (H1) is a constraint, if it is lower than the maximum height of the robot (H4>H1). In fourth example (Fig. 2.10) it is targeted to design a camera mechanism (as an example) for existing garbage-collecting robot. This example described here to show that our aim in this thesis is not ,only, limited to mechanical design of whole robot, but also it can be applied to design necessary parts which should be installed to the existing robot. The environmental niche and relative constraint, for this example can be itemized as follows:
Environmental niche:

- A flat surface (Direct-physical meaning)

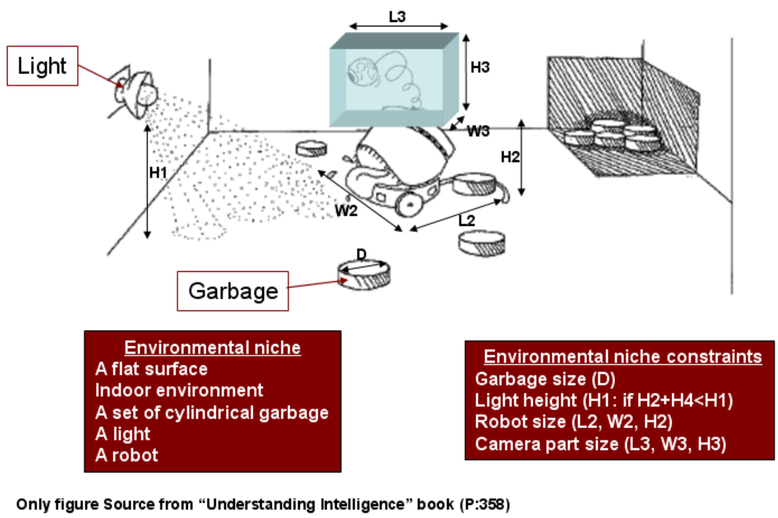


Figure 2.10: Forth example of garbage-collecting robot. It is targeted to design a camera mechanism (as an example) for existing robot.

- Indoor environment (Direct-physical meaning)
- A set of cylindrical garbage (Direct-physical meaning)
- A light (Direct-physical meaning)
- Size limitation (it is considered based on the game rules) (Indirect-physical meaning)

Environmental niche constraint:

- Garbage size (D) (Direct-physical meaning)
- Light height (H1: if $H2+H4<H1$) (Direct-physical meaning)
- Robot size (L2, W2, H2) (Indirect-physical meaning)
- Camera part size (L3, W3, H3) (Indirect-physical meaning)

In this case the "existing robot" is considered as a environmental niche, because the size of robot has direct effect to the design of the camera mechanism. Also limitation in the existing hardware to accept the additional sensors or motors can be recognized as constraints of environmental niche.

In this approach the all design parameters that they affect a mechanical design, can be considered as a environmental niche and relative constraint, and applied to the process of design through the fourth Mechanical Design Principle presented in next section.

2.4 Mechanical Design Principles: "Mecha-telligence Principles"

In this thesis the concept of "intelligent mechanical design" is presented to show how a mechanical structure can be design to have an effect to the robot controllability, simplification and its tasks performance. The description of this concept will lead us to establish the landmarks of the territory of mechanical designing in the form of seven design principles. The design principles, named "Mecha-telligence principles", provide a guidance on how to design autonomous mobile robots mechanics. They incorporate the insights gained in this large design field in a compact and coherent form. Macha-telligence principles guide us in asking the right questions when investigating issues concerning a self-controllable, reliable, realizable, and compatible mechanic for autonomous mobile robots (see fig. 2.11).

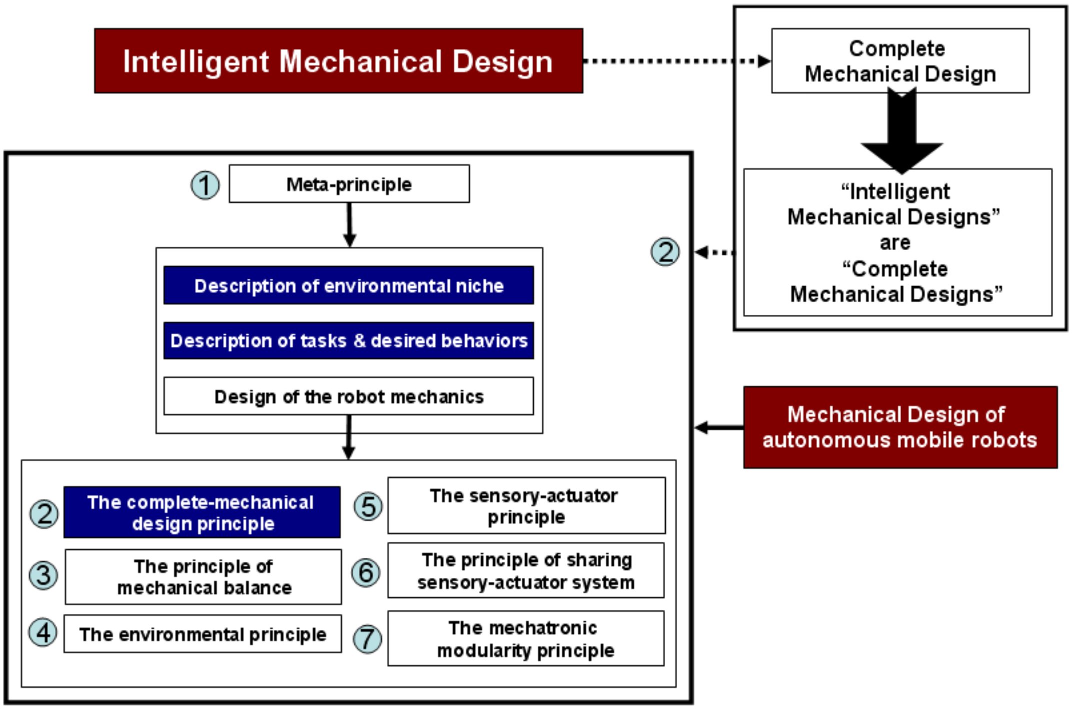


Figure 2.11: Overview of design principles of mechanical design of autonomous mobile robots.

Principle 1: The three-constituents principle[3]

Designing mechanical parts of autonomous mobile robots always involves three constituents: (1) definition of environmental niche, (2) definition of desired behaviors and tasks, and (3) design of robot mechanics. Constituents (3), design of robot mechanics, has been split into design principle 2 through 7. A mechanical design problem can be started as follows: Given intended environmental niche and the desired behaviors, how do we design the mechanical parts of robot? Alternatively it can be proceeded as follows: we already have a robot with a particular architecture. Also we have a particular environmental niche. For a new desired behaviors or task which mechanism or mechanical part is necessary to add to the robot and how do we design them?

Principle 2: The complete-mechanical design principle

The complete-mechanical design principle states that intelligent mechanical designs are complete. Recall from section 2.3 that complete mechanical designs are self-controllable, reliable, realizable, and compatible.

[3]This principle is described based on the "principle 1" presented in UNDERSTANDING INTELLIGENCE book (P:302), mentioned in subsection 2.2.3. Here we selected some part of their description with minor change regards to our concept in this thesis.

Principle 3: The principle of mechanical balance

The mechanical balance principle has two aspects: First it states that the complexity of the mechanical design has to match the complexity of the robot desired behaviors. Second it states that a robot mechanics should be designed as a part of a system not arbitrarily. It must be done when the sensory system and also hardware architecture are considered.

Principle 4: The environmental principle[4]

The environmental principle states essentially two things: "First, it implies exploiting the physics of the system-environment interaction. Second, it means exploiting the constraints of the environmental niche". The environmental principle is one of the significant principles that has direct effect to the mechanical design simplicity and reliability. In many different cases (Specially "competition" and "ordering" cases) the mechanics of the robot have to be designed in such a way to satisfy all environmental niche constraints regard to the game rules or user requested, when the robot usability is considered. Also, in our experiences in different projects, we realized that any kinds of limitation in design parameters (even user requests such as cost and operating life-time) can play a very important role in designer's perspective and creativity. Therefore, for all of these, we integrated all possible design parameters in form of "environmental niche" and "environmental niche constraints", explained in detail earlier in section 2.3. In this approach the all design parameters that they affect a mechanical design, can be considered as a environmental niche and relative constraint, and applied to the process of design through "the environmental principle".

Principle 5: The sensory-actuator principle

The sensory-actuator principle states that the *type* and *position* of the sensors and actuators in a system can have direct effect to the robot functionality, performance, simplicity, and reliability. In different cases by designing or selecting the proper and sufficient sensors and actuators, also, their position in the system, the performance and functionality of the robot can be higher than a case that the design is performed without considering this principle. Also the number of actuators and sensors used in the system can be affected by applying this principle in the mechanical design process (contributing with the principle of sharing sensory-actuator system).

[4]This principle is described based on the principle of "Cheap design" presented in UNDERSTANDING INTELLIGENCE book, mentioned in subsection 2.2.3. In definition of the environmental principle we selected two of three aspects of principle of "cheap design" regards to our concept in this thesis. Third aspect of cheap design principle, *designing parsimoniously* , is used in description of the principle of sharing sensory-actuator system but different meaning and approach compare with the concept mentioned in this book.

Principle 6: The principle of sharing sensory-actuator system

The principle of sharing sensory-actuator system means designing parsimoniously in point of view of actuators and sensors number. For detail understanding of this principle we refer to the three examples described in this thesis (chapter 3, 4, and 5)

Principle 7: The mechatronics modularity principle

The mechatronics modularity principle states that the robot should have a modular architecture in its electronics and mechanics. This principle can be significant role in the mechanical design reliability mentioned in the second principle, "the complete mechanical design principle" and, also, easy maintenance. Modularization process always involves three steps: First: description of the robot system architecture. In this step designer needs to have or make the architecture of the robot system in form of flowchart. Visualization can help the designer's perspective to realize what the robot is includes and how can work as a system. Second, defining the possible module (single module). Based on the flowchart provided in previous step, the possible module should be defined by considering the similar hardware structures and the similar mechanical connections. Third, merging the single modules to a merged module. The basic idea underlying in this step is to extend the "modularity" concept by merging the "single modules" into the "merged modules" aiming at the decreasing of the number of wires.

2.5 Mechanical Design Process: "Mecha-Telligence Methodology"

To show how the Mecha-telligence principles can be applied on the processes of the design of autonomous mobile robots mechanics, we proposed a novel methodology, "Mecha-telligence" methodology (see Fig. 2.12). Mechanical design in the proposed methodology is done based on preference of classification of the robot specification described by interaction of the robot with its environment and, also, the physical parameters of the robot mechatronics itself (principle 1). In this approach the robot specification is classified to a set of high-level- and low-level-specifications which can be expressed as tasks (desired behavior) and physical parameters of the robot, respectively. In fact the high-level-specification, including the two layers: main and sub layers, is described by considering the robot tasks and its interaction with the environment in which it is used. A low-level-specification may, consecutively, consist of a set of layers explaining the physical setup of the robot, its body, sensory, and motor systems. A main goal in these analyzing process of the robot specification is that figuring out to a Mono-spec layer (the last layer of low-level-specification) including a simple basic

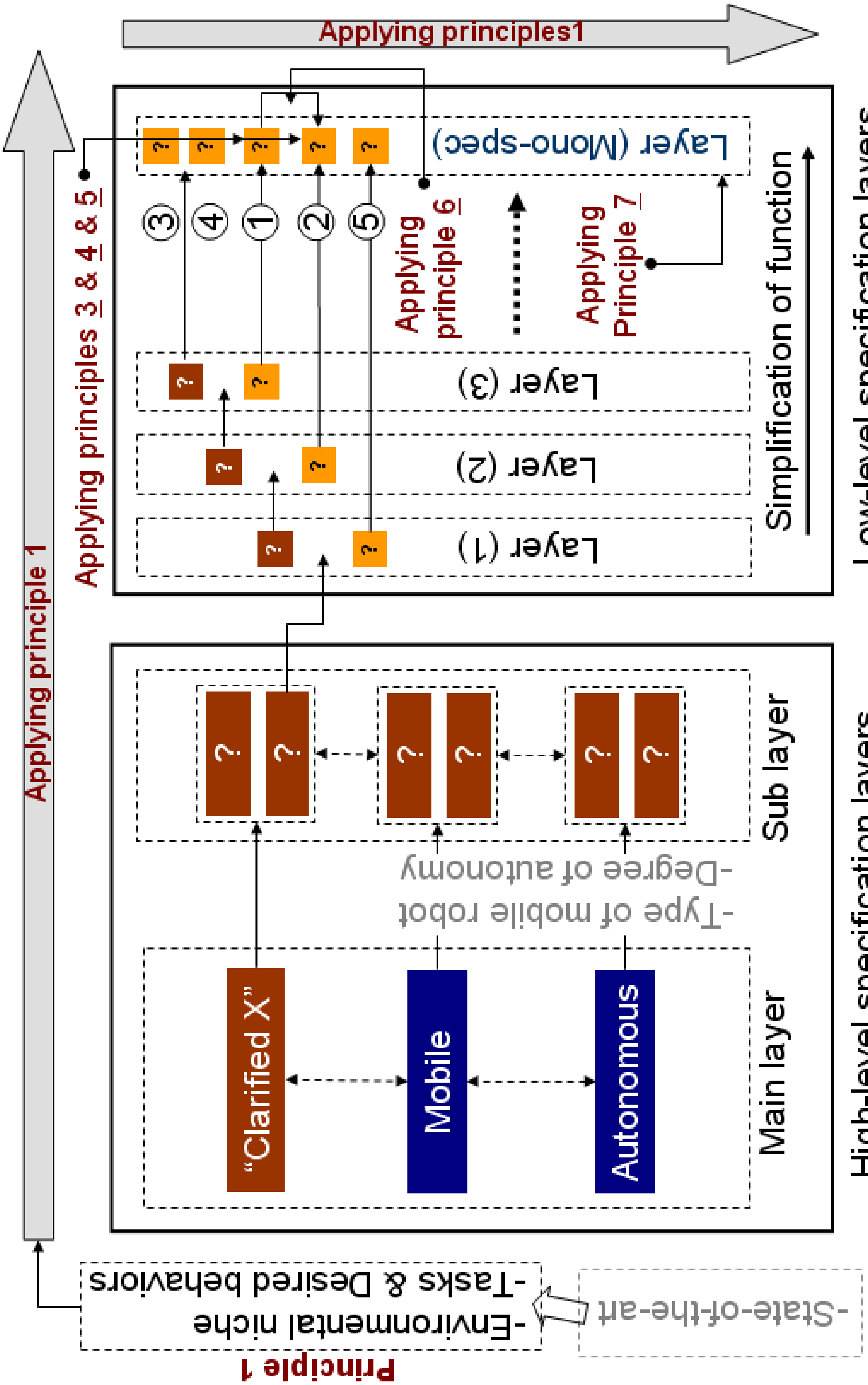


Figure 2.12: Overview of "Mecha-telligence methodology" for mechanical design of autonomous mobile robots with defined task "X".

function or selecting a sensor for a single task or behavior. The mechanical design will be started based on an important defined robot mono-spec, and then, mono-spec design will be extended to the other mono-specs by adding the minimum actuators and sensors to the design (principle 6). In each step of the design process we are trying to come up to a proper solution by considering the robot morphology, design of the suitable actuators, by applying the description of environmental and physical-morphological constraints, and by employing passive mechanisms which have inherent intelligence characteristics (principle 3 and 4) . In this methodology the mechanical design will be finalized by considering the proper and sufficient positioning of sensory-motor system (principle 5) and concept of modularity in robot mechatronics (principle 7).

Chapter 3
Soccer Robot

Chapter 3

Soccer Robot

3.1 Introduction

ROBOCUP is an international joint project to promote AI, robotics, and related field. It is an attempt to foster AI and Intelligent robotics research by providing a standard problem where wide range of technologies can be integrated and examined. RoboCup chose to use soccer game as a central topic of research, aiming at innovations to be applied for socially significant problems and industries. The ultimate goal of the RoboCup project is by 2050, develop a team of fully autonomous humanoid robots that can win against the human world champion team in soccer [5]. "Hibikino-Musashi" is a joint middle-size league RoboCup [6, 7] soccer team. Members of the team are from three different research and educational organizations[1], all located in the Kitakyushu Science and Research Park, Kitakyushu, Japan.

In this chapter we introduce our approach to realize a simple, robust, and valuable platform for "Musashi robots". "Musashi" robots, presented in this thesis, are series of autonomous mobile soccer robots which have fully mechatronics modular architecture including a strong ball-kicking device with capability of lifting the ball and a ball-holding mechanism, aiming at getting champion in RoboCup Midsize League. "Musashi" robot, including an omni-directional moving mechanism, an omni-vision and a novel ball-kicking-lifting-holding device, can be presented as a reliable and robust soccer robot with high degree of simplicity, mobility, and maneuverability. In this approach we show that selecting a proper mechanical moving mechanism and a suitable vision system can lead to realize a reliable, simple, and low cost robot comparing with the first version of our car-like soccer robot included many different kinds of sensors and a complex design structure. The main focus in this theses, with regard to this project, is on detail design and developing process of a strong kicking device with ca-

[1]The three organizations are: Kyushu Institute of Technology, The University of Kitakyushu, and Kitakyushu Foundation for the Advancement of Industry Science and Technology.

pability of shooting (up to 5 [m/s]), lifting (up to 120 [cm]), and holding the ball. The ball-kicking is accomplished by designing an unique spring charging mechanism called "Cam Charger".

3.2 Summary of design based on "Mecha-telligence methodology"

In this section the mecha-telligence methodology will be described for design and implementation of an autonomous mobile soccer robot.

3.2.1 Description of the basic terms

The aim of this project is to participate in the international robot competition "RoboCup Midsize League". The first step in "Mecha-telligence methodology" as shown in Fig. 2.12 is to describe the tasks, desired behaviors, environmental niche, and environmental niche constraints. Let's start from a basic question: "what is ROBOCUP?"

RoboCup is an international joint project to promote AI, robotics, and related field. It is an attempt to foster AI and Intelligent robotics research by providing a standard problem where wide range of technologies can be integrated and examined. RoboCup chose to use ***soccer game*** as a central topic of research, aiming at innovations to be applied for socially significant problems and industries [5].

Robot task

By considering the aim of RoboCup, *"playing soccer"* can be recognized as the robot's task.

Desired behavior

Based on "RoboCup Midsize League" rules and common sense about soccer, the desired behaviors can be described to three following items:

- Put the robot in the field
- Robot gets the desired commands (such as start the game, corner kick, throw in, and etc) sent by a referee from a host computer via wireless communication.
- Robot moves, searches for the ball, carries a ball, avoid to crash to other robots and kicking the ball to the opponent goal autonomously.

Environmental niche and relative constraints

Alternatively, regard to "RoboCup Midsize League" rules, the environmental niche and the relative constraints can be defined and itemized as follows: (Fig. 3.1)

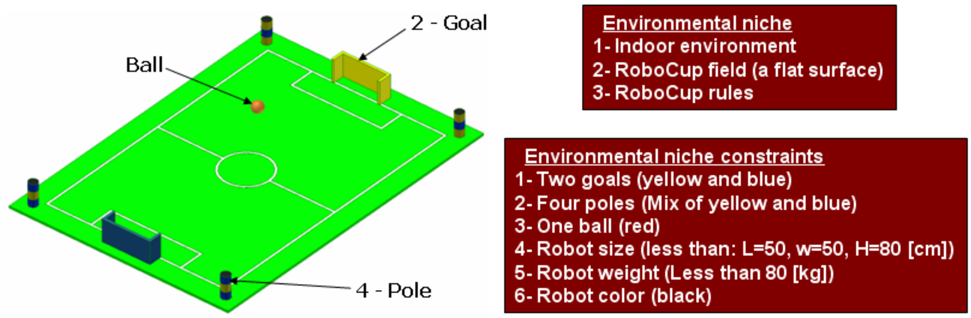


Figure 3.1: The definitions of environmental niche and the relative constraints (Soccer robot).

Environmental niche:

- A flat surface (Direct-physical meaning)
- Indoor environment (Direct-physical meaning)
- RoboCup field (a flat surface) (Direct-physical meaning)
- RoboCup rules (Indirect-physical meaning)

Environmental niche constraint:

- Two goals (yellow and blue) (Direct-physical meaning)
- Four poles (Mix of yellow and blue) (Direct-physical meaning)
- One ball (red) (Direct-physical meaning)
- Robot size (less than: L=50, w=50, H=80 [cm]) (Indirect-physical meaning)
- Robot weight (Less than 80 [kg]) (Indirect-physical meaning)
- Robot color (black) (Indirect-physical meaning)

Degree of autonomy and mobility

Robots should perform all actions necessary to play soccer, completely, autonomously without human intermediary. Only the start, stop, and desired commands will be sent via wireless communication to the robots by a side-referee. Robots have to be designed as a wheel type-untethered robot (Fig. 3.2).

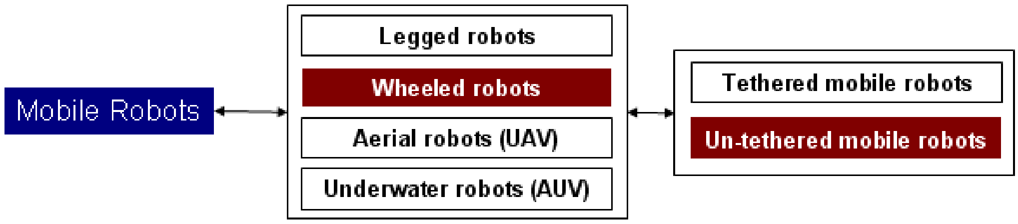


Figure 3.2: The selected type of soccer robot.

3.2.2 Simplification process of design functions

High-level specification layers (Main layer and Sub layer)

Regard to the description of four above terms, the high-level specification layers including main-layer and sub-layer can be illustrated as Fig. 3.3.

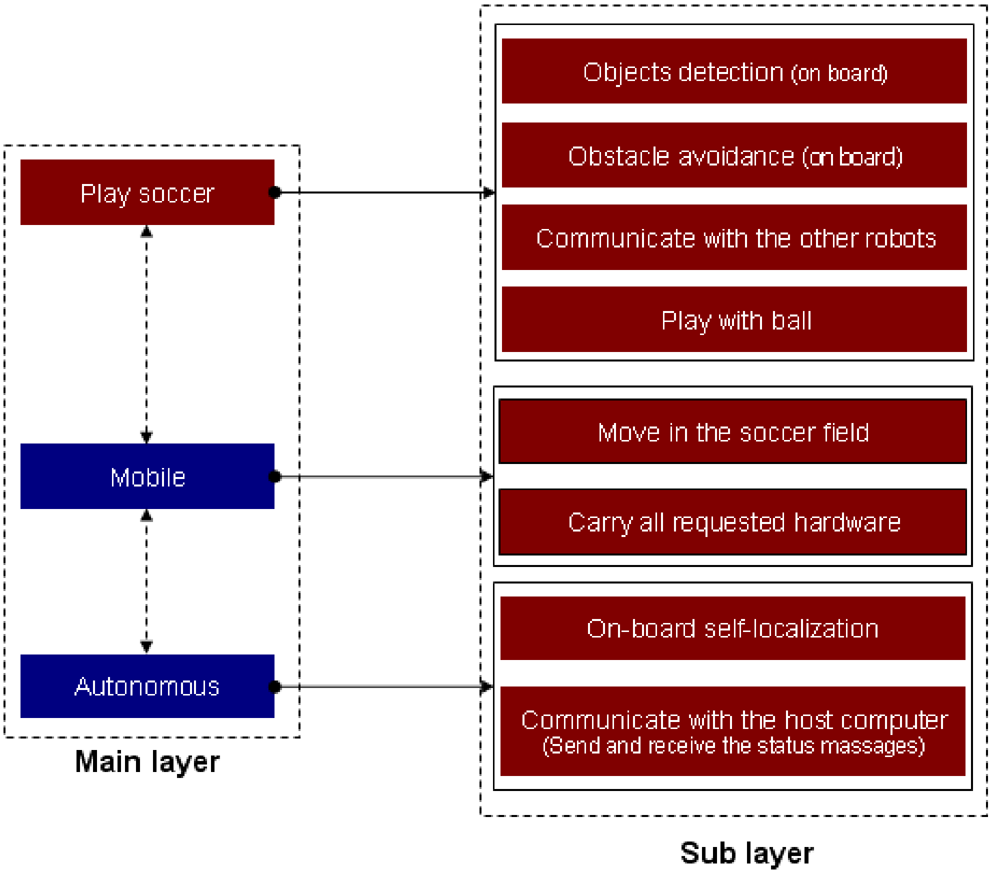


Figure 3.3: The high-level specification layers including main-layer and sub-layer (Soccer robot).

Low-level specification layers (Layer 1, layer 2, and mono-spec layer)

Figures 3.4, 3.5, and 3.6 show the generation of layer 1, layer 2, and mono-spec layer, respectively. In this three figures the red color shows the terms which are on the process of simplification, white color illustrates the terms that are not important for our design purpose, and yellow color indicates the terms which recognized as a simple basic function or selecting a sensor for a single task or behavior.

Functions priority of design

Figure 3.7 shows the result of our simplification process from "main layer" to "mono-spec layer". Also, this figure illustrates the function design priority in point of view of mechanical parts design.

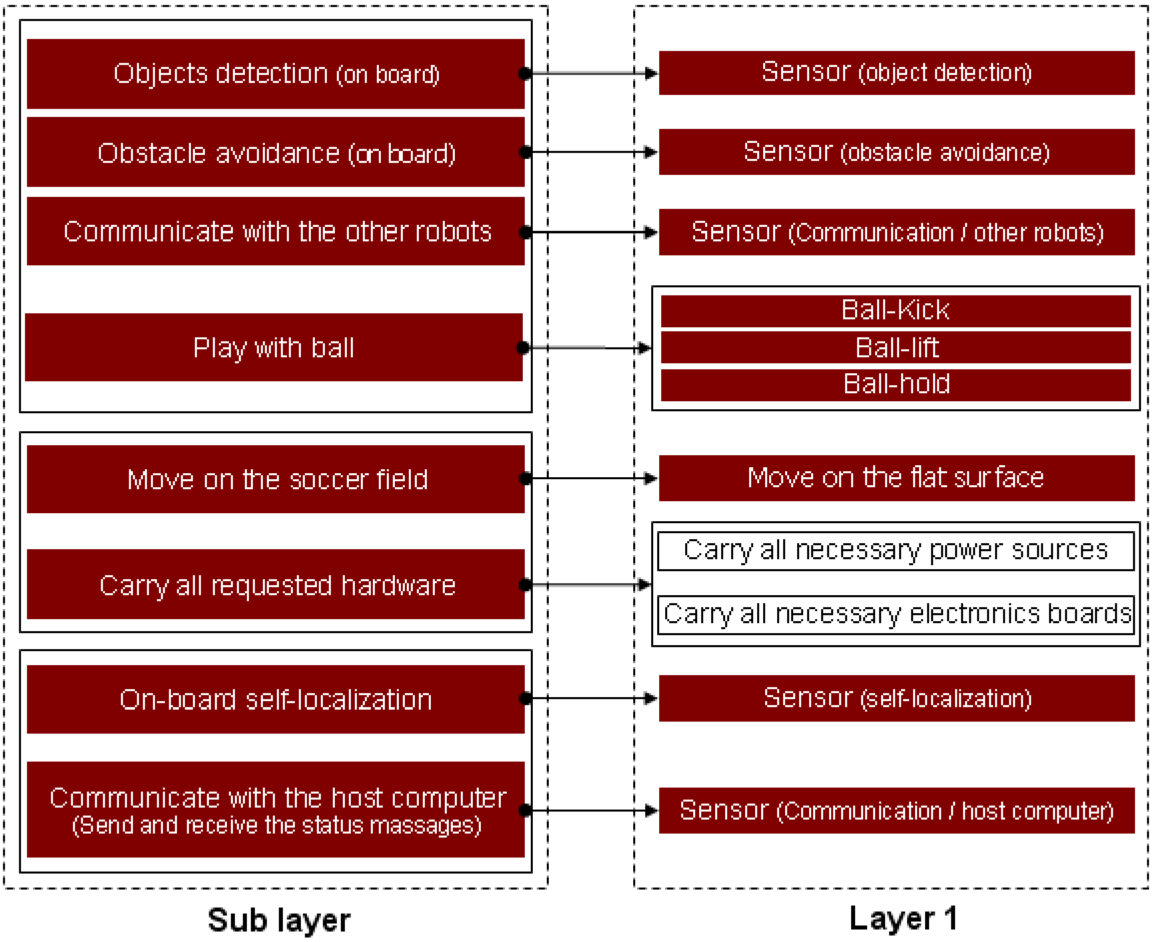


Figure 3.4: Layer 1 generated from the sub-layer (Soccer robot).

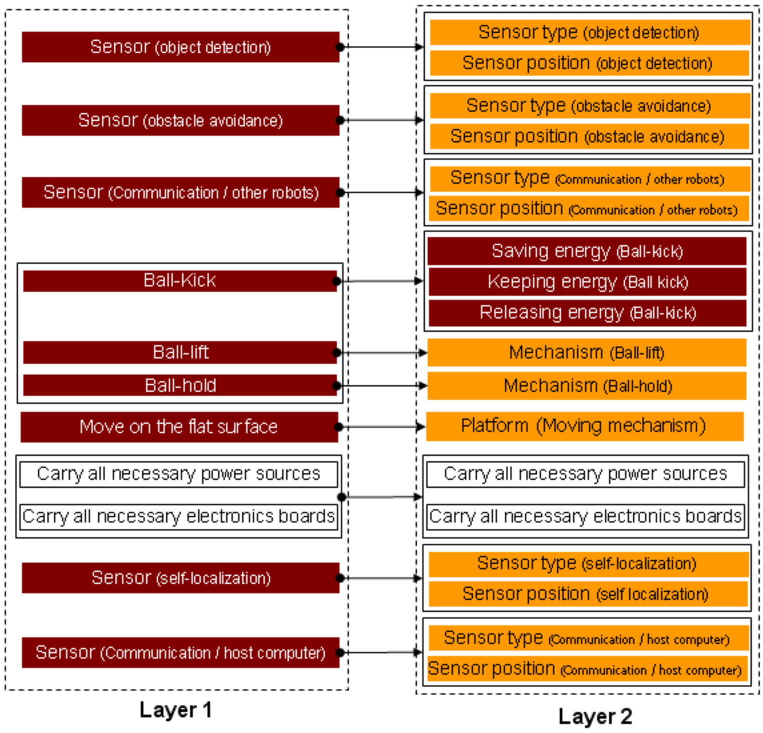


Figure 3.5: Layer 2 generated from the layer 1 (Soccer robot).

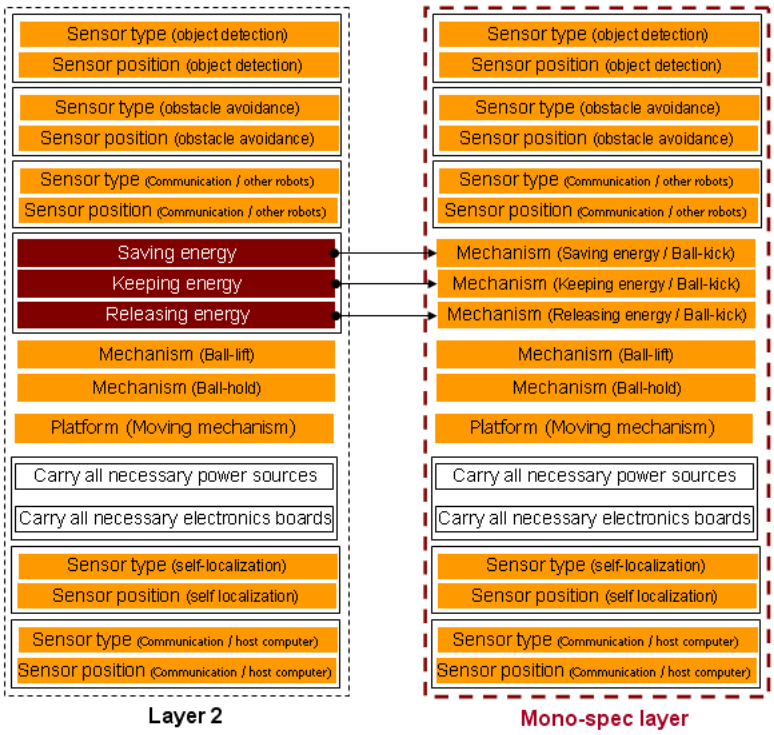


Figure 3.6: Mono-spec layer generated from the layer 2 (Soccer robot).

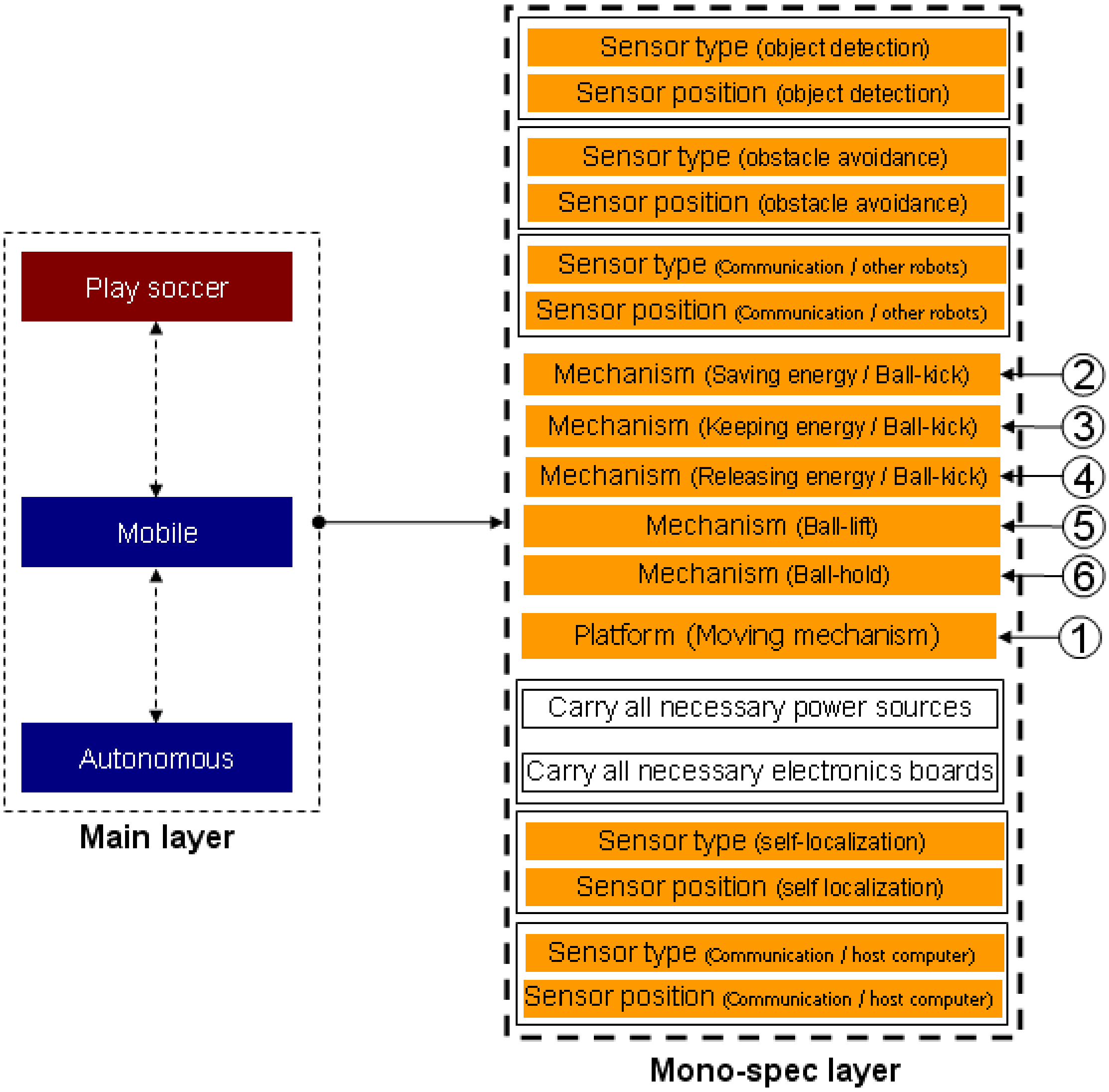


Figure 3.7: Results of the mono-spec layer generation and the function design priority (Soccer robot).

3.2.3 Design process: Applying the "mecha-telligence principle"

This sub-section provides, only, an overview to our robot design and its architecture. Also it shows how the "mecha-telligence principles" have been applied in the process of the design. The whole detail designs and all definition and description of the related concepts are explained in the next sections. To deep understanding about our approach and detail of the robot design, reading the these sections is recommended.

Designing function 1

By surveying on the proper existing mechanisms and considering the principle 3 (The

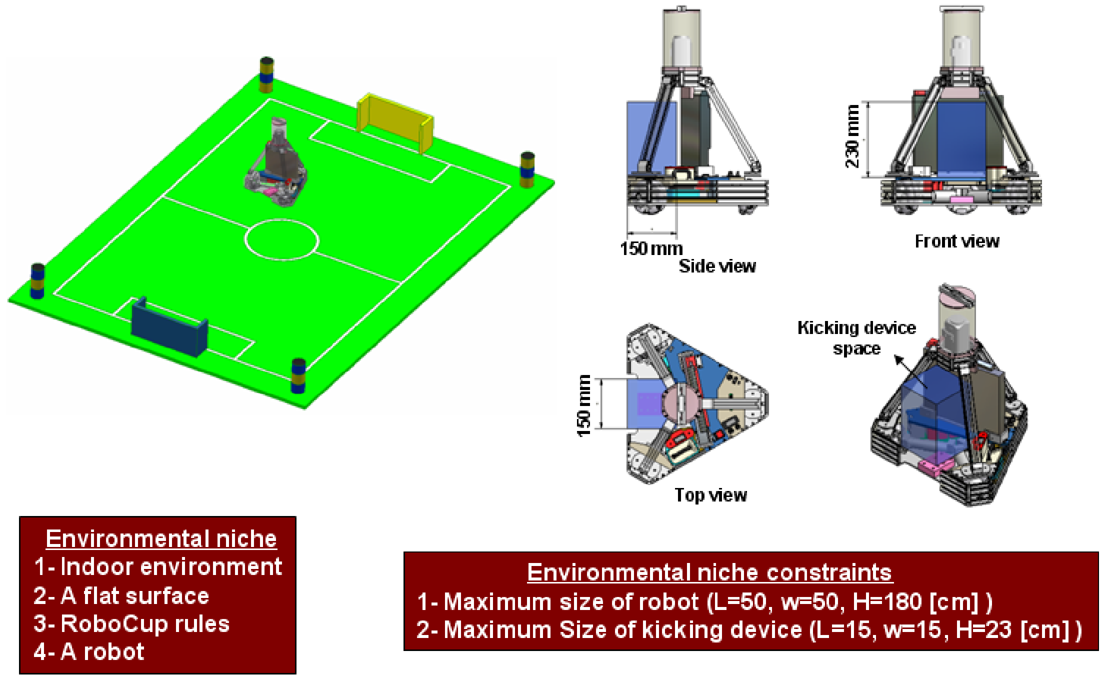


Figure 3.8: The definitions of environmental niche and the relative constraints (Kicking device).

principle of mechanical balance), we designed an omni-directional platform for our robot, called "Musashi robot". The dynamical and kinematic characteristics of the design allows for a high maneuverability in the field, easy controllability for programing, and expected reliability and compatibility (Principle 1: The complete-mechanical design principle) for the robot. Robots have been designed in such a way to satisfy the three environmental constraints, size, weight and color (Principle 4: the environmental principle).

Designing function 2 to 6

For the design of the kicking device, we must assume that we have a robot with the particular architecture. We can now ask what kinds of kicking device should be designed to fit in the robot and satisfy the our requirements. Therefore the "environmental niche" and "environmental niche constraints" are different and can be defined as follows: (Fig. 3.8)
Environmental niche:

- Indoor environment (Direct-physical meaning)
- A flat surface (Direct-physical meaning)
- RoboCup rules (Indirect-physical meaning)

- A robot (Indirect-physical meaning)

Environmental niche constraint:

- Robot size (less than: L=50, w=50, H=80 [cm]) (Indirect-physical meaning)
- Maximum size of kicking device: L=310, w=93, H=188 [mm] (Indirect-physical meaning)

By considering the second constraint of the environmental niche (*Applying principle 4*) and implementation of *principle 3*, we developed a strong kicking device with capability of shooting up to 5 [m/s]. The ball-kicking is accomplished by design of an unique spring charging mechanism called "Cam Charger". In this novel kicking device, "Cam Charger" mechanism has been designed instead of three mechanisms to save, keep and release the energy of a series of torsion springs just using a motor and a limit switch (*Applying principle 5*). The functionality of this ball-kicking mechanism is extended to lift the ball up to 120 [cm] by adding an edge to the kicker plate (*Applying principle 6*) and hold the ball by installing a simple linkage mechanism inside of the Cam Charger mechanism. This linkage mechanism is actuated and controlled by the same motor and limit switch used for ball-kicking (Applying principle 5 & 6). (For detail description, please refer to the next sections)

Designing other functions

Object detection, collision avoidance, and self localization were performed by selecting an omni-directional camera as a robot's vision sensor, installed in the top of the robot (Applying principle 5). An on-board wireless network device installed on the robot's PC is used for robot communication with host computer and also other robots.

For easy understanding of what we did and what we designed, the results are visualized in Fig. 3.9. The black color shows our solutions for the listed problems in the mono-spec layer. Note that we could realize all functions, only, by selecting a proper moving mechanism (Omni-directional mechanism), a suitable vision system (Omni vision), and designing a novel charging spring mechanism (Cam Charger).

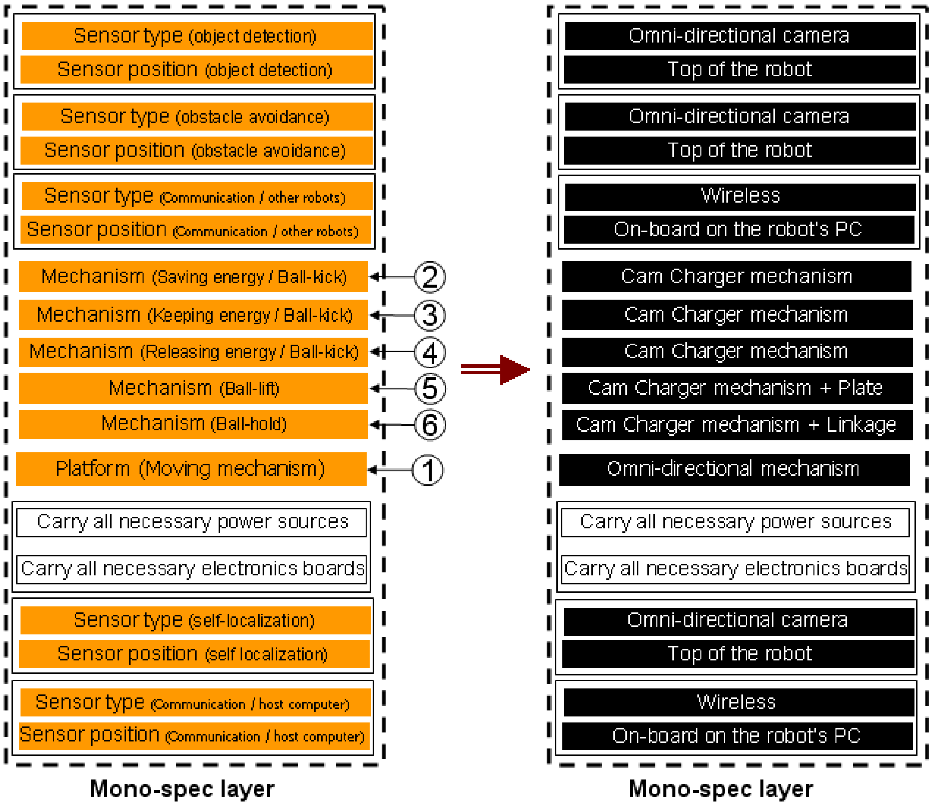


Figure 3.9: The results of design (Soccer robot). The black color shows our solutions for the listed problems in the mono-spec layer.

3.3 Concept of Designing "Musashi" Robot

Figure 3.10 shows the first version of our robot, which is purchased from "Frounhofer AIS (Institute Autonomous Intelligent System)". This robot has a car-like locomotion mechanism including two active wheels and two castor wheels in back and front, respectively. A digital camera attached 70 [deg] wide-angle lens is mounted the top of the robot that can rotate 360 [deg] around it's axis, actuated a DC motor and controlled using an absolute encoder. Because, the robot is used in the dynamic environment, for obstacle avoidance, the robot is also equipped with different kinds of sensors such as two IR sensors, two distance sensors, and touch sensors as shown in fig. 3.10. Also, a pneumatic kicker is installed on the robot which is supplied by two small air pressure tanks. Regard to above explanation about the mechatronics design of the robot, the existing problems can be itemized as follows:

- (a) Poor mobility functions to perform the requested motion such as rotate around the ball or lateral movements.
- (b) Complex data processing and sensors reading regard to sensor fusion.

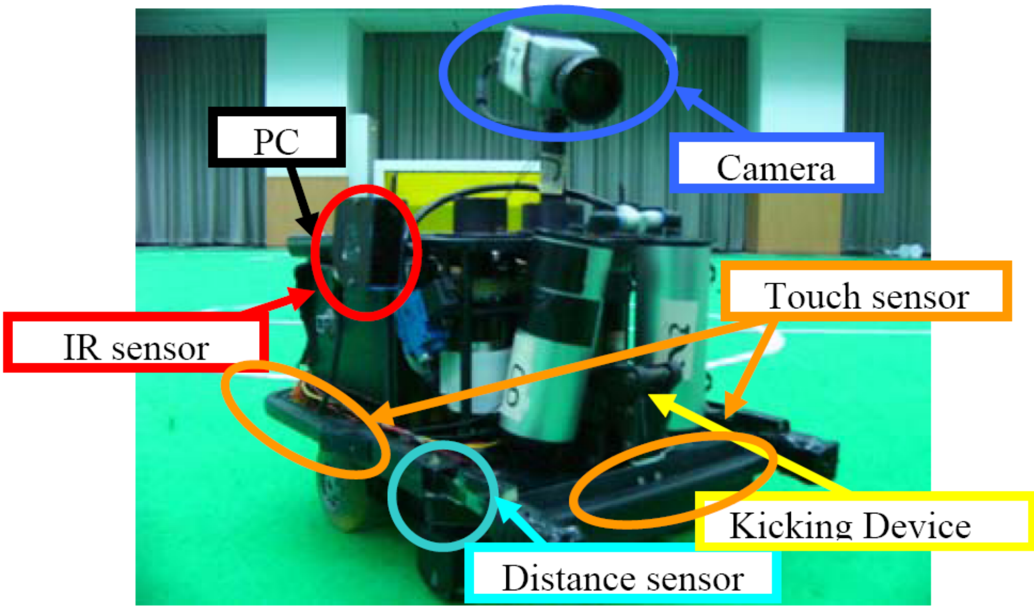


Figure 3.10: The first version of “Hibikino-Musashi” team robot equipped with eleven sensors

- (c) Complexity of the camera motion includes designing hardware, software, and its control.
- (d) Low reliability and not enough robust for a dynamic environment such as RoboCup.
- (e) Complex mechatronics system in consideration of difficulties of assembling, maintaining, extendability, and transporting.
- (f) Low speed ball kick, comparing with the other team’s robots which can shoot the ball in high speed up to 6.0 [m/s] [8, 9].

In order to solve above mention problems and achieve the required characteristics for the RoboCup scenario and develop generic hardware platform for mobile robotic research and teaching, a new model of a mobile robot, named “Musashi” robot, is completely designed and constructed by “Hibikino-Musashi” team members. In this design approach we show that selecting a proper mechanical moving mechanism, a suitable vision system, and mechatronics modular architecture design can lead to realize a reliable, simple, and low cost robot comparing with the previous car-like robot included many kinds of sensors and a complex design structure in its hardware and software.

3.4 “Musashi” robot architecture

“Musashi” robot is designed based on two significant and fundamental concepts: “omni-directional" and "modularity" concepts (Applying principle 7: The mechatronic modularity principle).

3.4.1 "Omni-directional" concept

"Musashi" robot includes an omni-directional platform, an omni-vision (Fig. 3.11). The dynamical and kinematic characteristics of the design allow for a high maneuverability in the field. The 3D mechanical CAD drawings were done with Autodesk Inventor and the mechanical parts are completely manufactured by "Hibikino-Musashi" team members. Each robot is equipped with 3 omni-wheels, each of them driven by a 70 [W] DC motor. Gearboxes with reduction rations of 18:1 are used to reduce the high angular speeds of the motors (7000 rpm) and to amplify the wheel's mechanical torques. The velocity feedback is done by using 540 [ppr] digital incremental encoders. The velocities of the wheels are controlled by three Faulhaber motor drivers (MCBL 2805) that each one has a RS232 communication port. The controllers read the pulse trains from the motor encoders and produce amplified PWM output voltages for the motors based on a PID algorithm. The result is a mobile robot with maximum linear speed of 1.9 [m/s] and acceleration of 2.5 [m/s^2]. In this approach, we could figure out the first problem (a) mentioned in section 3.3.

The problems (b) and (c) are considered, by changing the mono-directional vision (the vision system of the first version of our robot) to the omni-directional vision

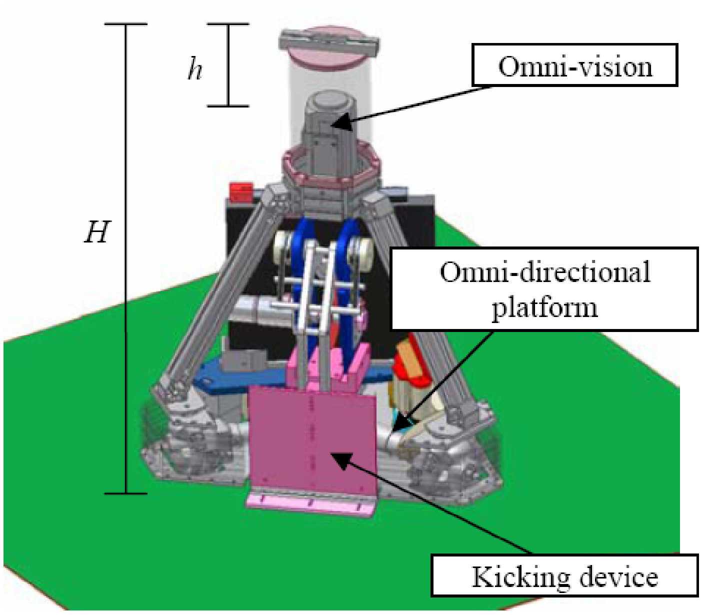


Figure 3.11: "Musashi" robot includes an omni-directional platform, an omni-vision, and a strong novel ball-kicking device, designed by Autodesk Inventor 3D-CAD.

Table 3.1: Specification of "Musashi" robot

Dimensions	Triangle 500 [mm] Height 500
Weight	16.0 [kg]
Actuator	Maxon 24.0 [V] 70 [W] DC-Motor x 3 Faulhaber motor driver x 3 Omni-wheel x 3
Battery	LiPolymer battery 3.7 [V] 2000 mAh x 7
Duration	0.5 h
Sensor	Omni-direction camera DC-motor encoder x 3

system consisting of a digital camera (IEEE 1394) and a hyperbolic mirror. The main parameters which should be considered and, carefully, chosen are the height of the mirror (H) and distance of between mirror and the camera (h) as shown in a Fig. 3.11. They also determine the viewing angle of the lens for a full-size image of the mirror [10]. In this approach, the omni-camera can be used, not only, for object detection and localization, but also for fully collision avoidance, comparing with our first robot that is requested the different types of sensors to avoid in contact with the other robots. As shown in Table 3.1, only sensors using in 'Musashi" robot are an omni-directional camera and three DC motor encoders comparing with the first version of our robot that was equipped with 11 sensors (two IR sensors, two distance sensors, a camera, two DC motor encoders, touch sensors, two limit switches for robot fingers, and an absolute encoder for camera motion). Figure 3.12 shows flowchart of "Musashi" robot power system including a main Li-Polymer battery (25.9 [V]) and an extra Li-Polymer battery (7.2 [V]) using for high acceleration and speed during catching and carrying the ball. The necessary voltage for the camera and the micro computer power supply are produced by converting 25.9 [V] to 12.0 [V] and 5.0 [V], respectively. The power consumption of the robot is approximately 40 [W], and, the operation duration of the robot is estimated to be 0.5 [h].

3.4.2 "Modularity" concept

1. First step: Description of the Robot System Architecture

To describe and emphasize the "modularity" concept, in the first step, it is necessary

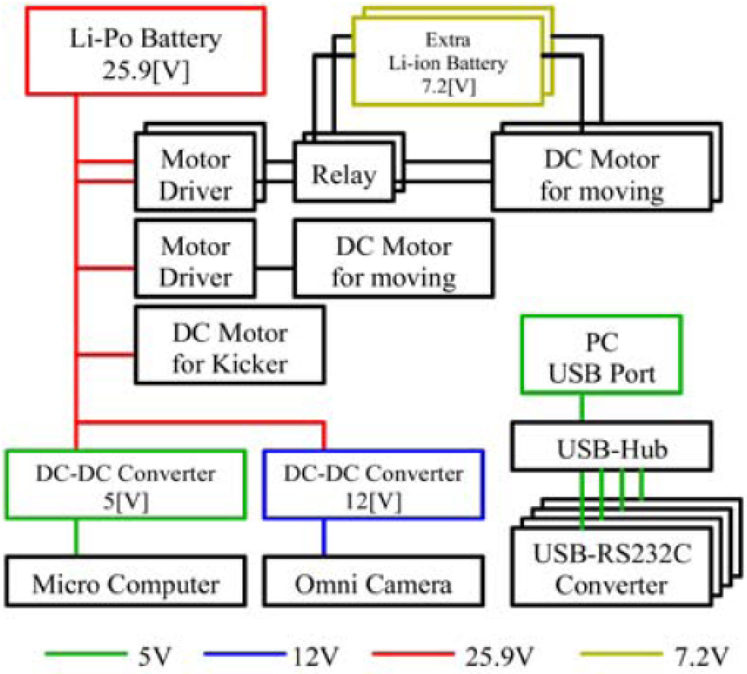


Figure 3.12: Flowchart of "Musashi" robot power system.

to have a short overview to the robot system architecture design. "Musashi" robot is equipped with a laptop on which the image processing, the control and the communication and data exchange are performed. Behavior commands such as start, stop, corner kick, and etc. are received by a referee box PC, located out of the field, via on-board wireless LAN. To achieve a safe, simple and robust system, the robot is adopted using three different transport protocols: IEEE 1394, USB, and RS232. The communication between omni-directional camera and laptop PC, installed on the robot, is performed using IEEE 1394 (FireWire). The laptop PC sends the motor control commands (target velocity) to the motor drivers via USB protocol. However, the motor drivers have only RS232 protocol port, we use three USB/RS232 converters between PC and motor drivers (Fig. 3.13-a, note: Considering with no color). Additionally, a USB/RS232 converter is used between PC and the circuit of kicking device.

2. Second step: Defining the possible modules (single module)

Regard to the flowchart of the robot architecture, the possible modules should be defended by considering the similar hardware structures or similar mechanical connections. Figure 3.13-a shows the six possible modules, illustrated with six different colors, which can be defined for "Musashi" robot hardware. For examples, USB hub and USB/RS232 converters can be selected to be a module (USB module), because they have a close hardware structure (Fig. 3.13-b). Also, because there is a mechanical connection between each omni-wheel and each shaft of the motor, MW modules can be defined. One of the significant considerations in the process of a simple module design is that: **"The module should be designed to have connector/s as an I/O port/s"**. The connector/s should be fixed to the body of the module except of special cases that fixing the connector is not possible or it requests the complex design

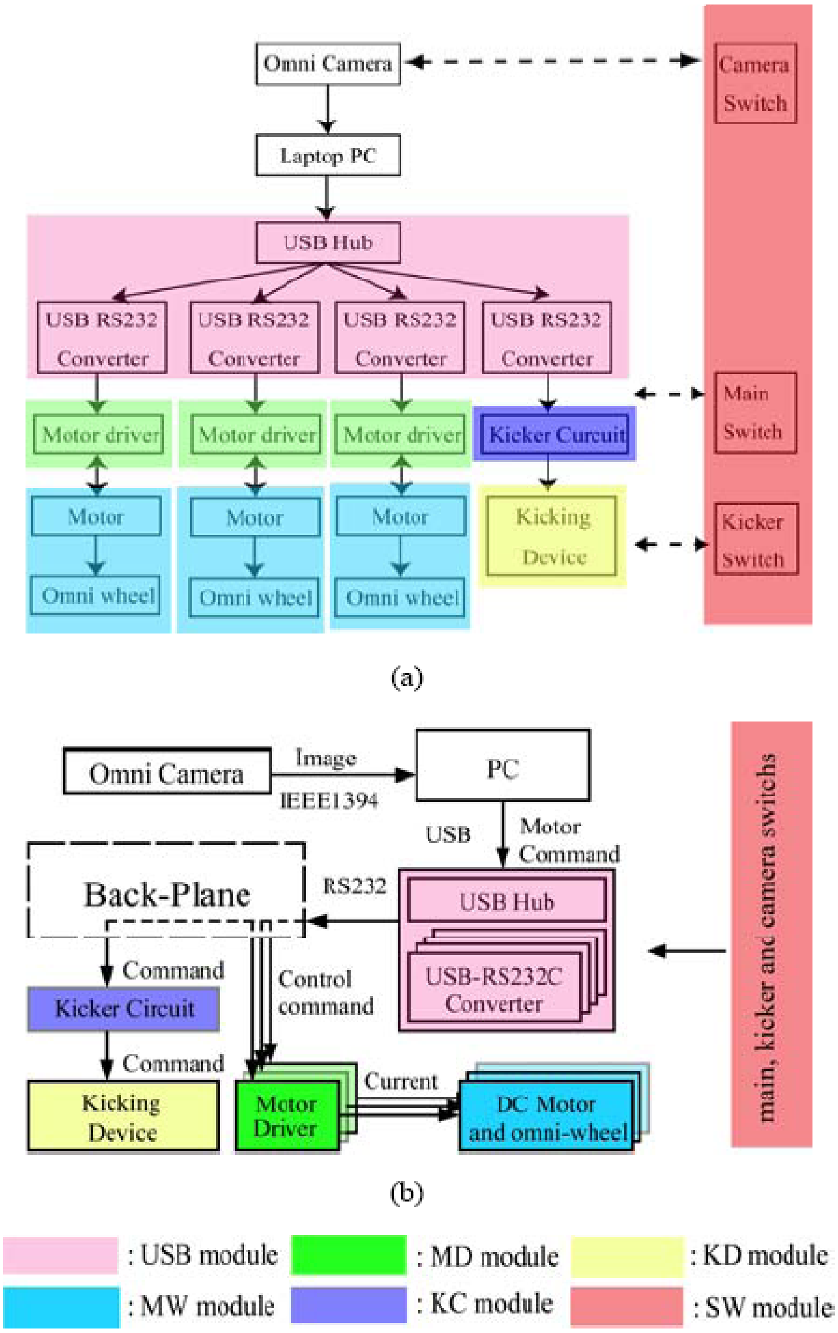


Figure 3.13: System architecture of "Musashi" robot. (a) Shows the possible modules. (b) Shows the result of single modules.

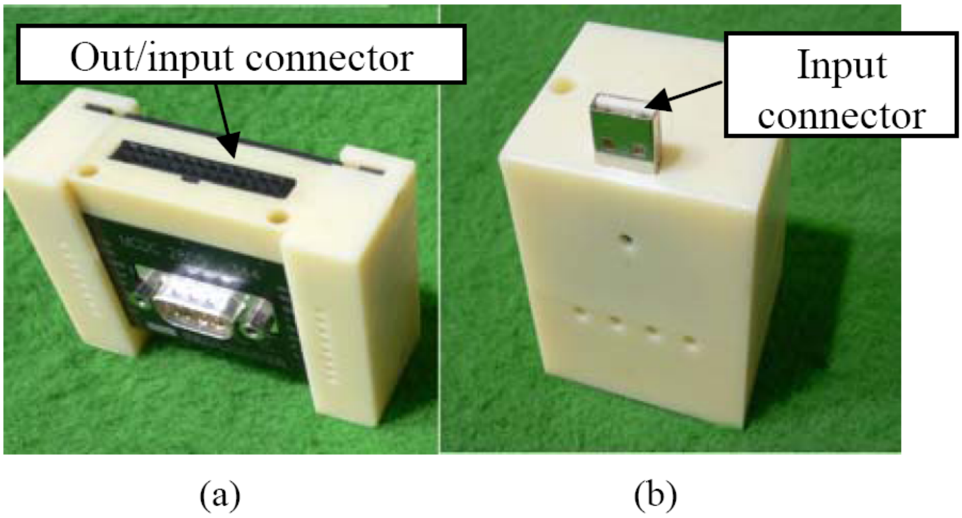


Figure 3.14: (a): Motor driver module (MD module) including a connector as I/O port. (b): USB module consists of two connectors for input and output port. Output connector is not visible in the figure.

or expensive manufacturing. Figure 3.14-a,b show the developed motor driver module (MD module) and USB module, respectively. USB module (Fig. 3.14-b) has an output connector same as connector of the MD module in its bottom side that it is not visible in the figure.

3. Third step: Merging the single modules (merged module)

The “modularity” concept can be extended by merging the single modules into each other (called merged modules), aimed to decrease the number of the wires that they should be used for connection between the single modules. A “merged module” can be defined by considering the flow chart connections of the “single” modules and can be accomplished by design and implementation of the “back plane” concept. A back plane can be functioned as a “single” modules communication port for a “merged” module. For example, by considering the connection between the USB, KC and MD modules, illustrated in Fig. 3.13-b, a back plane can be designed to merge the five modules (an USB, a KC, and three MD modules) and solve the problem of the complex wiring connections. The new “merged” module is named “central controller module” (Fig. 3.15).

As a summary of “Musashi’ robot modular architecture: We designed the robot in two main modules, Bottom module and Upper module (Fig. 3.16), considering the easy assembling, maintaining, and transporting. Consequently, bottom module consists of six “single modules” (a switch, a battery, a kicking device, and three Motor-wheel modules) and one “merged module” (Central Control module). In this approach, we

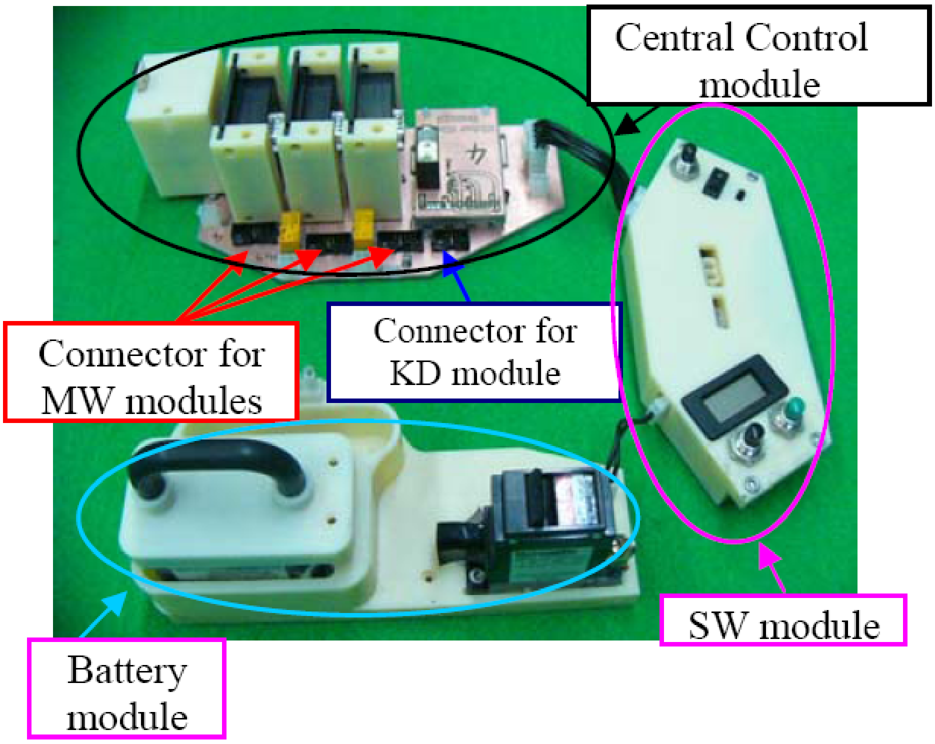


Figure 3.15: Modules of “Musashi” robot hardware.

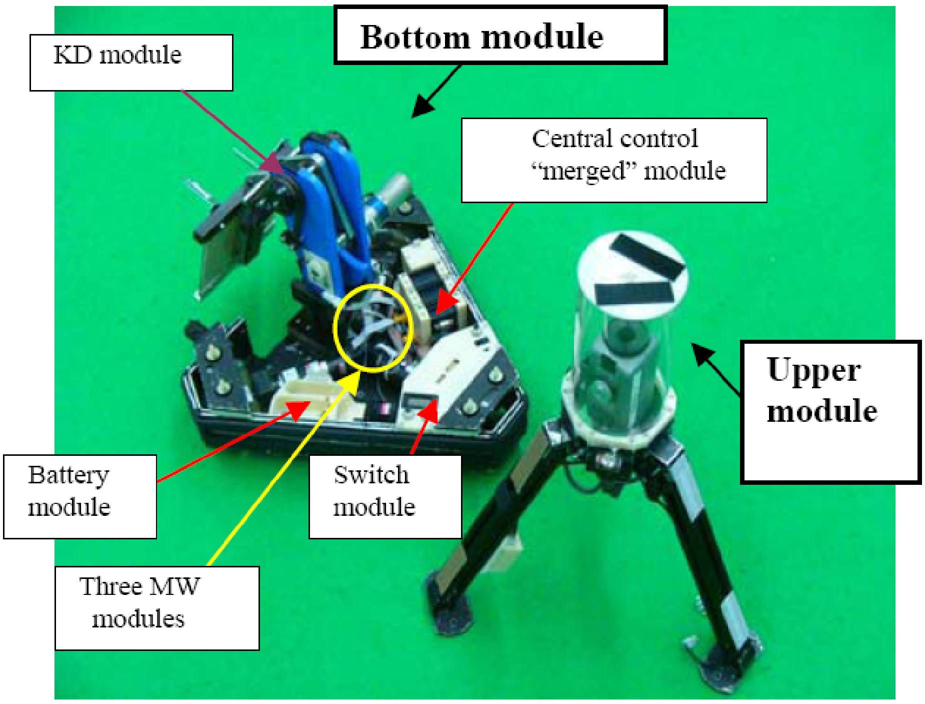


Figure 3.16: Modules of “Musashi” robot.

could solve two problems (d) and (e) mentioned in the section 3.3.

3.5 Strong novel kicking device

The first official RoboCup games and conference was held in 1997. In total 40 teams participated on the competitions, seven of them participated in the RoboCup Mid-size league (MSL). In that year the robots had no kicking device and they were, only, able to carry the ball to the inside of the goal. One year later (the second RoboCup game, 1998), Freiburg team had made the first kicking device in the history of the RoboCup and became champion. After this year, developing the kicking device became a key point for all the participated teams, so that, many researchers put their efforts to develop kicking devices with stronger than as possible. For example, Freiburg team made a kicking device, in 2000, which worked with spring, much faster than their first solenoid type of shooting device, or in 2002, Philips team developed a spring type kicking device with high speed (about 6 [m/s]). In that time, GMD-MUSASHI team (our team) had a robot including a pneumatic kicking device with capability of shooting the ball about 2 [m/s] (Fig. 3.10). The new developed kicking device has high performance, so that, the kicking device can speed the ball up to 6 [m/s] and lift the ball about 1 [m].

3.5.1 Overview of the Different Types of Kicking Device

In general, the kicking devices can be classified in four different types in dependence of the activated force:

- The Solenoid kicking device
- The Pneumatic Kicking Device
- The Elastic Kicking Device
- The Spring Kicking Device

In this section, we only make an over view about advantage, disadvantage and basic operation of each type of kicking devices.

The Solenoid kicking device

As shown in Fig. 3.17, a solenoid consists of a coil and iron rode. If a current is applied, a magnitude flux will be produced which can pull the iron rode into the coil (PULE type) or push it out of the coil (PUSH type). This movement of the iron rode generates a force (F) which can be used as an motive force to activate the kicking device.

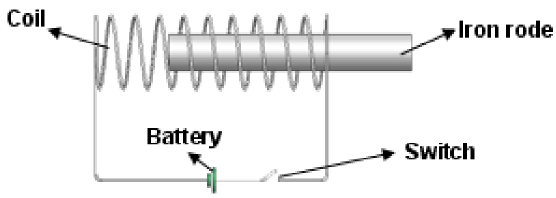


Figure 3.17: Schema of a solenoid.

Basic operation

Three methods are common in making a solenoid kicking device (see Fig. 3.18). The difference is dependence of, only, the position that the force of solenoid is applied.

Advantage

- High speed: In general solenoid can generate a very fast motion because of the characteristic of magnetic flux.
- Easy control: The control of a solenoid can be achieved by on/off a normal switch, located between a battery and the solenoid.

Disadvantage

- High current:Force in a solenoid and the speed of the iron rode depends on several parameters such as the material of the rode, the gap between the coil and the rode, and the number of turns of wire on the coil.
- High weight: Solenoid with capability of high force generation requested a heavy iron rode also many number of turns of wire, that totally make heavy device.

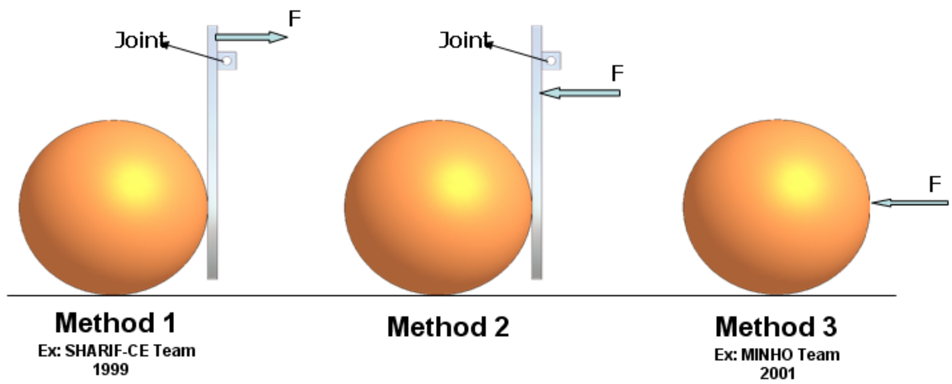


Figure 3.18: Three methods are common in making a solenoid kicking device. The difference is dependence of, only, the position that the force (F) of solenoid is applied.

The Pneumatic Kicking Device

Basic operation

Two methods are common in making a pneumatic kicking device (see Fig. 3.19). The difference is dependence of, only, the position that the force of solenoid is applied.

Advantage

- Low weight: With recent improvements in the pneumatic technology, new cylinders are produced to have light wight with high performance.
- Easy control: The control of a pneumatic cylinder is done by the solenoid. then, as mentioned before, the control of a solenoid can be *achieved by on/off a normal switch, located between a battery and the solenoid.*

Disadvantage

- High current: Force in a solenoid and the speed of the iron rode depends on several parameters such as the material of the rode, the gap between the coil and the rode, and the number of turns of wire on the coil.
- High weight: Solenoid with capability of high force generation requested a heavy iron rode also many number of turns of wire, that totally make heavy device.

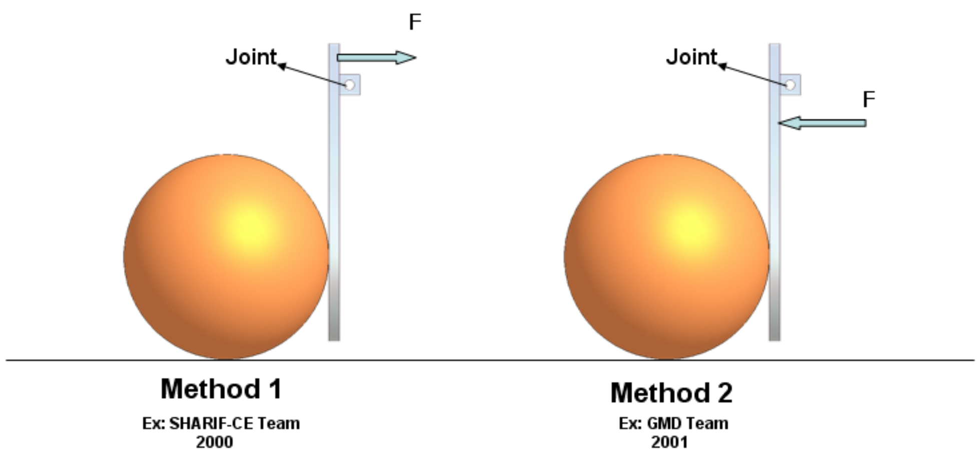


Figure 3.19: Two methods are common in making a pneumatic kicking device. The difference is dependence of, only, the position that the force (F) of the pneumatic device is applied.

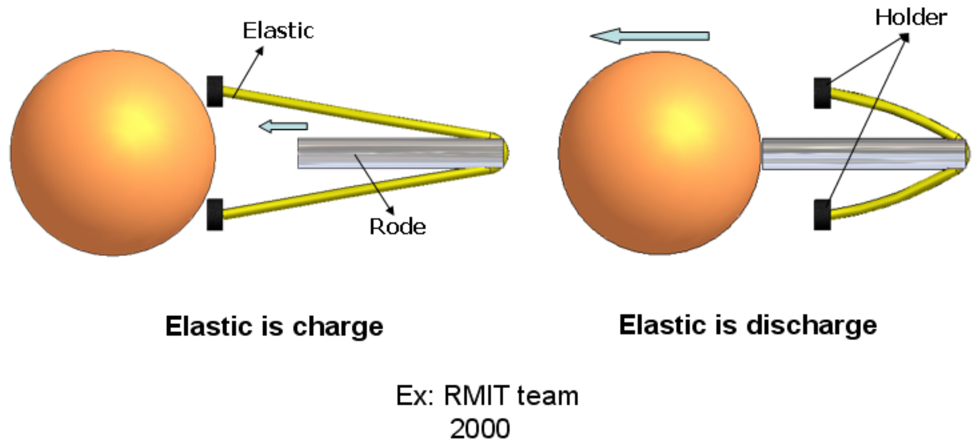


Figure 3.20: Basic operation of a elastic kicking device.

The Elastic Kicking Device

Basic operation

Figure 3.20 shows the basic operation of a elastic kicking device.

Advantage

- High speed: Since stored energy in a elastic can be released in a very short time, it is able to give a high speed to the ball.

Disadvantage

- Needs large space: Elastic kicking device requests a big area for operation and control.

The Spring Kicking Device

Basic operation

It depends on the designer can be completely different in basic operations. In fact, there is no concrete classification in these types of kicking devices. As an example, Philips team made a kicking device using a car-pressure spring (see Fig. 3.21) that it is able to shoot the ball more than 6 [m/s]. Amount of applied force by the plate of Philips kicking device, in the moment of hitting the ball, shown in Fig. 3.22. Figure 3.23 shows the spring mechanism of KIRC team from Japan in which is designed base on torsion springs.

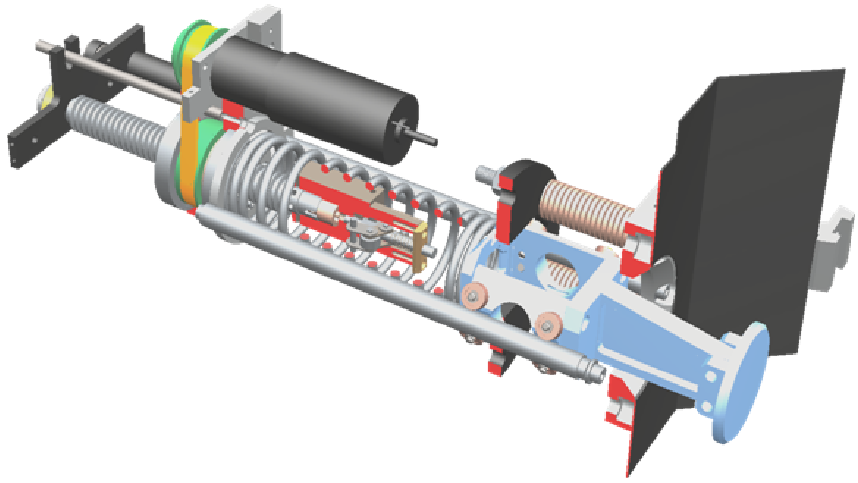


Figure 3.21: Schema of Philips kicking device [8].

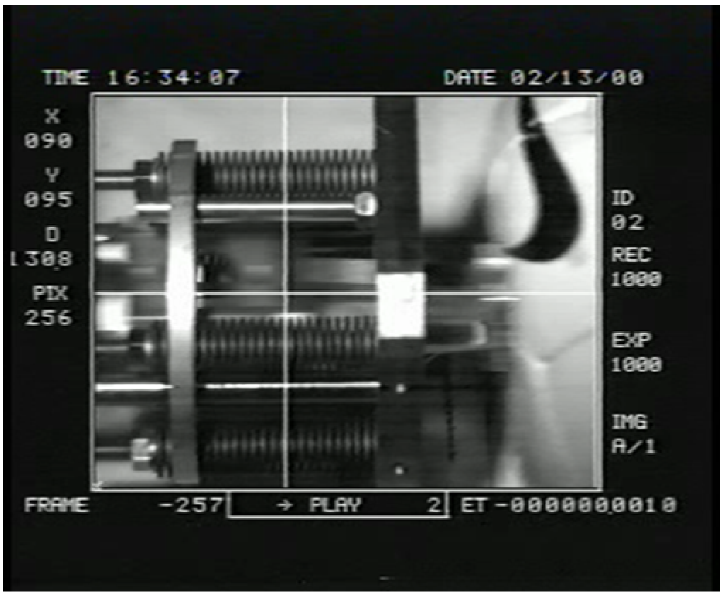


Figure 3.22: Amount of applied force by the plate of Philips kicking device, in the moment of hitting the ball.

Advantage

- High speed: Since stored energy in a spring can be released in a very short time, it is able to give a high speed to the ball.

Disadvantage

- Needs large space: Spring kicking device requests a big area for operation and control.

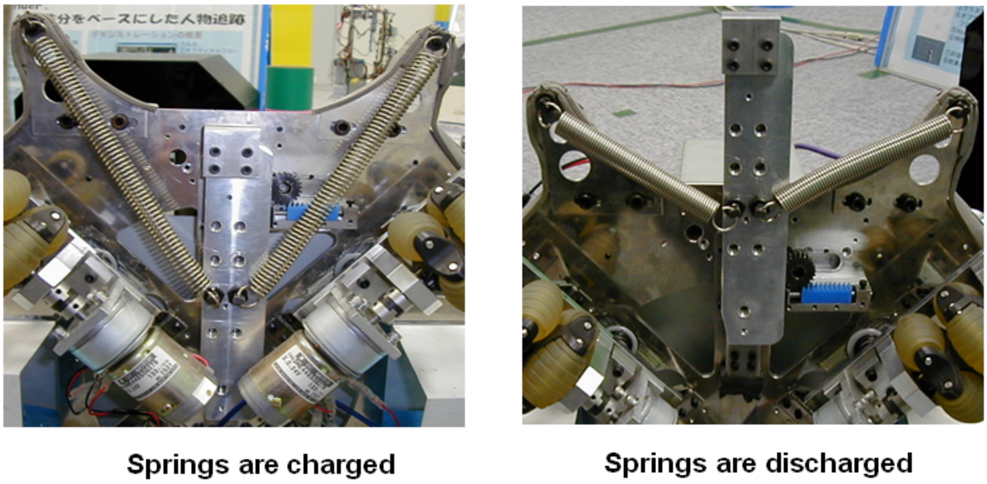


Figure 3.23: Kicking device of KIRC team (KIT, Izuka, Japan)

3.5.2 Design of New Kicking Device

Basic Concepts of Design

The new kicking device is designed based on two main functions and two environmental constraints:

- Function to shoot the ball with high speed as much as possible (Target about 5 or 6 [m/s])
- Function to lift the ball
- First environmental constraint: Very simple control (we had limitation in our current robot hardware. using one motor without encoder and a few limit switches are permitted)
- Second environmental constraint: Small size (We have limitation for space of kicking device in our current robot (see Fig. 3.24). As shown in Fig. 3.25 this space, roughly, are L=310 [mm], W=93 [mm], and H=188 [mm].

Regards to second environmental constraint and also robot shape, there is three possibilities to design a kicking device as shown in Fig. 3.26. We selected the third possibility because of limitation in space.

Principle of Design

In general three mechanisms are necessary to use energy of a spring:

- Mechanism to charge the spring (Saving energy)

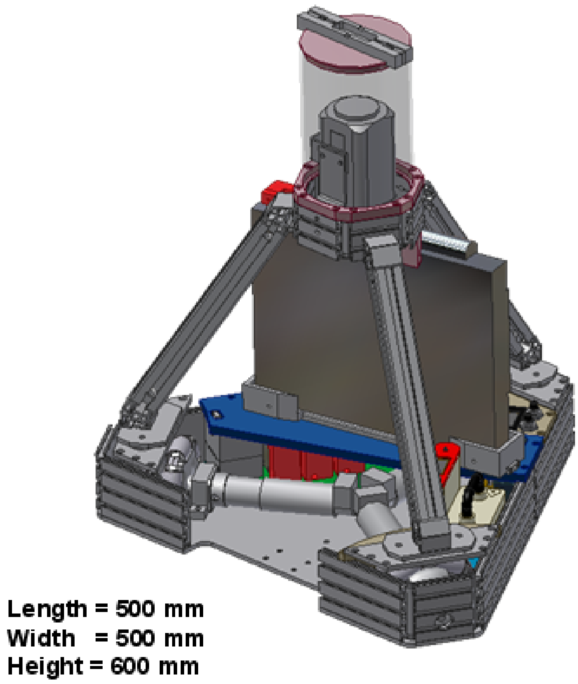


Figure 3.24: "Musashi" robot.

- Mechanism to lock the spring (Keeping energy)
- Mechanism to release the spring (Releasing energy)

In the developed novel kicking device presented in this section, we designed a mechanism instead of three mechanisms to save, keep and release the energy of a series of torsion springs just using a motor and a limit switch.

Saving energy

A cam mechanism use to charge the torsion springs and save the energy. The basic concept of this mechanism shown in the Fig. 3.27. With regard to the eqs. (3.1) and (3.2), the motive force (F) to charge the torsion spring is minimized while the force (F) is perpendicular to the axes (m) (β =90°) where the torque τ_S takes a certain value.

$$F = \frac{\tau_S}{X \cdot sin\beta} \tag{3.1}$$

$$\beta = 90^\circ \Longrightarrow F_{min} = \frac{\tau_S}{X} \tag{3.2}$$

The main function of the special designed cam is keeping the angle β 90° during the spring charging process (Fig. 3.28). Then the torque of motor τ_C, needed to charge the spring, will be minimized as following equation:

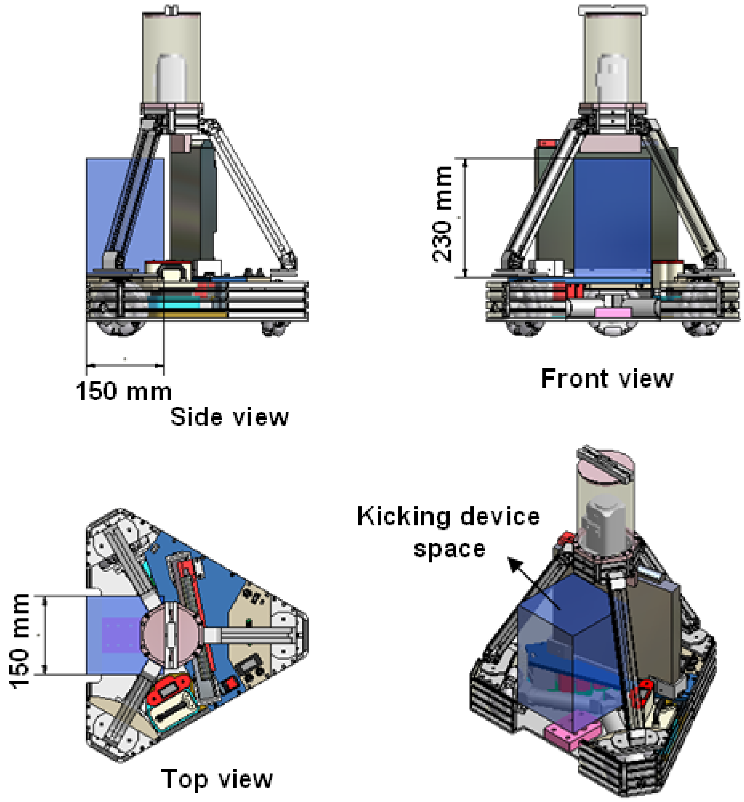


Figure 3.25: New kicking device should be designed to fit to the size of L=150 [mm], W=150 [mm], and H=230 [mm].

$$\tau_{C\,(min)} = F_{min} \cdot d \tag{3.3}$$

where d is the perpendicular distance between the direction of contact force F (line N) and the center of the cam C. The distance d can be calculated with the following equations:

$$Line\,M: \;\; y = x \cdot tan\theta \tag{3.4}$$

$$Line\,N: \;\; x \cdot cos\theta + y \cdot sin\theta + l_1 = 0 \tag{3.5}$$

$$d = \frac{-l_1 cos\theta - l_2 sin\theta + l_1}{\sqrt{cos^2\theta + sin^2\theta}} = -l_1 cos\theta - l_2 sin\theta + l_1 \tag{3.6}$$

Here, l_1 is the length of OG, and the angle θ is the angle between the line OG and the line M. And the force F and τ_C can be obtained as following:

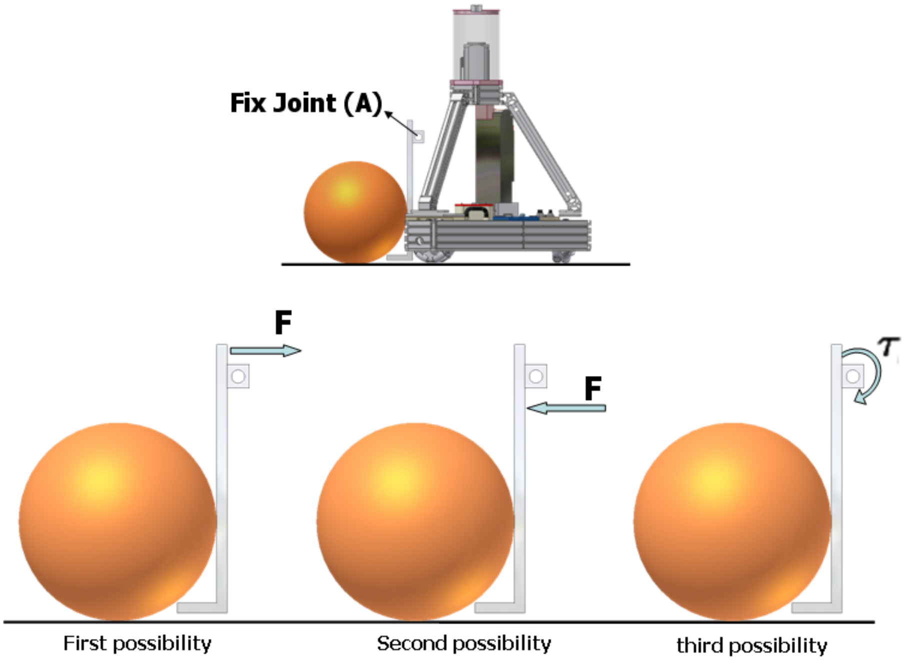


Figure 3.26: Three possibility to design a new kicking device.

$$F = \frac{\tau_S}{l_1} = \frac{nk\alpha}{l_1} \tag{3.7}$$

$$\tau_C = F \cdot d = nk\alpha(1 - cos\theta - l_2 sin\theta / l_1) \tag{3.8}$$

Where n is the number of springs, k is the stiffness coefficient of springs and α is the charging angle of springs. In this mechanism, during the charging time, the perpendicular distance between the direction of contact force F and the center of the cam (d in

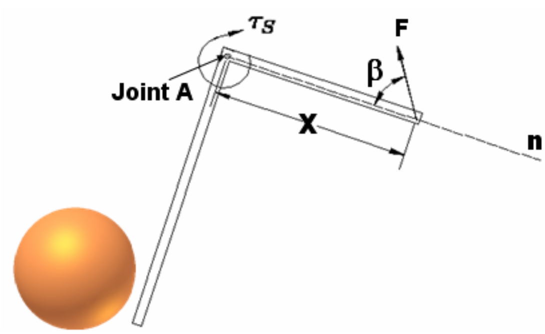


Figure 3.27: Basic concept of cam charger mechanism. Joint A is fixed and the torsion springs, as a resistance torque, are mounted in this joint. τ_S= spring torque (resistant torque), F = Motive force , X= distance between joint A and the point where force F is applied, and β= angle between force F and the direction of n

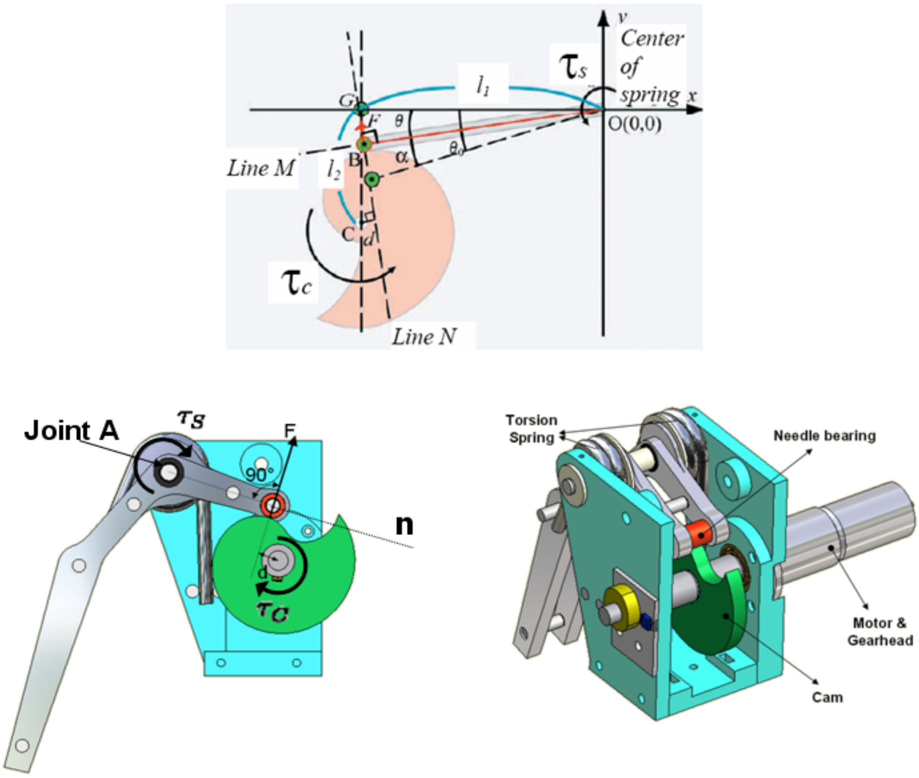


Figure 3.28: The coordinate and relation between the cam and the torsion spring. The main function of the cam is keeping the β angle 90 degree in during the spring charging process.

Fig.3.28) decreases when the spring torque (τ_S) and the contact force (F) increase. The red line in Fig.3.29 shows the derivation of motor torque relative to the charged angle of springs. The important point is that when the spring is charged more and more,

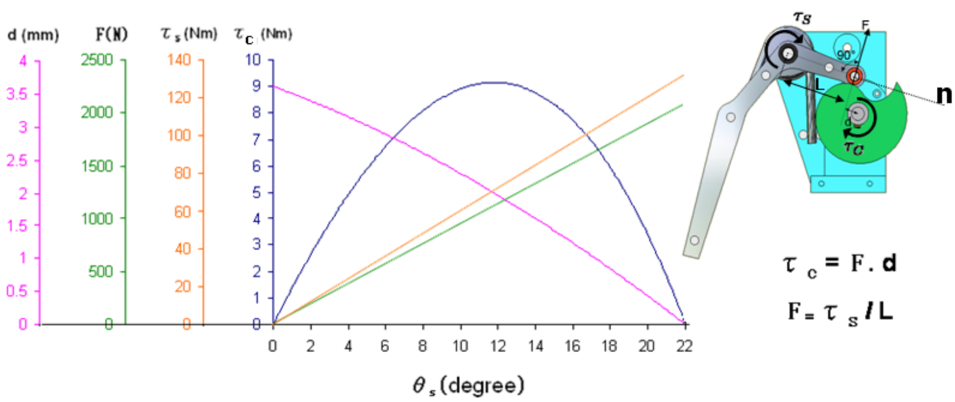


Figure 3.29: The derivation of motor torque τ_C (blue graph) and spring torque (orange graph) respect to the charged angle of spring α where n= 2, k=3.0 [Nm/deg], α = maximum 22 [deg], l_1=50 [mm] and l_2=50 [mm].

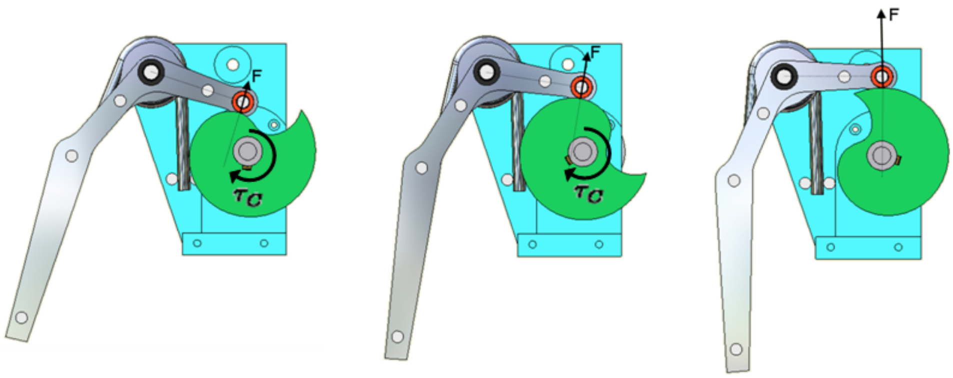


Figure 3.30: Shows the sequence of charging of springs in begging, middle, and end of the charging process. In the end of process of charging because of the direction of force F passes the center of the cam, the mechanism has inherent characteristics to lock.

the required motor torque is getting less and less in the second half of the graph in Fig.3.29. This mechanism makes charging very strong series of torsion springs possible with a small motor. As an example in case of a cam charger with specification $n=2$, k=3.0 [Nm/deg], α = maximum 22 [deg], l_1=50 [mm] and l_2=50[mm], for charging the 125 [N.m] resistance torque of two springs, we only need a motor-gearhead which can produce almost 9 [N.m] torque as a peak.

Keeping energy

In this mechanism, when spring is charged full, because of the direction of the force F passes the center of the cam, if the motor stops, the mechanism will lock. Then we can keep the energy of springs (See Fig. 3.30).

Releasing energy

It is clear when the motor continues to rotation (see Fig. 3.30) after the locking process; the spring will be released.

Ball-lifting Mechanism

Figure 3.31 indicates our simple solution to lift the ball (*Applying the principles 4 and 6*). By changing the width of the edge-plate we can adjust the parameter of lifting the ball up to 120 [cm].

Ball-holding Mechanism

Figure 3.32 illustrates our simple linkage mechanism, installed inside of the cam charger

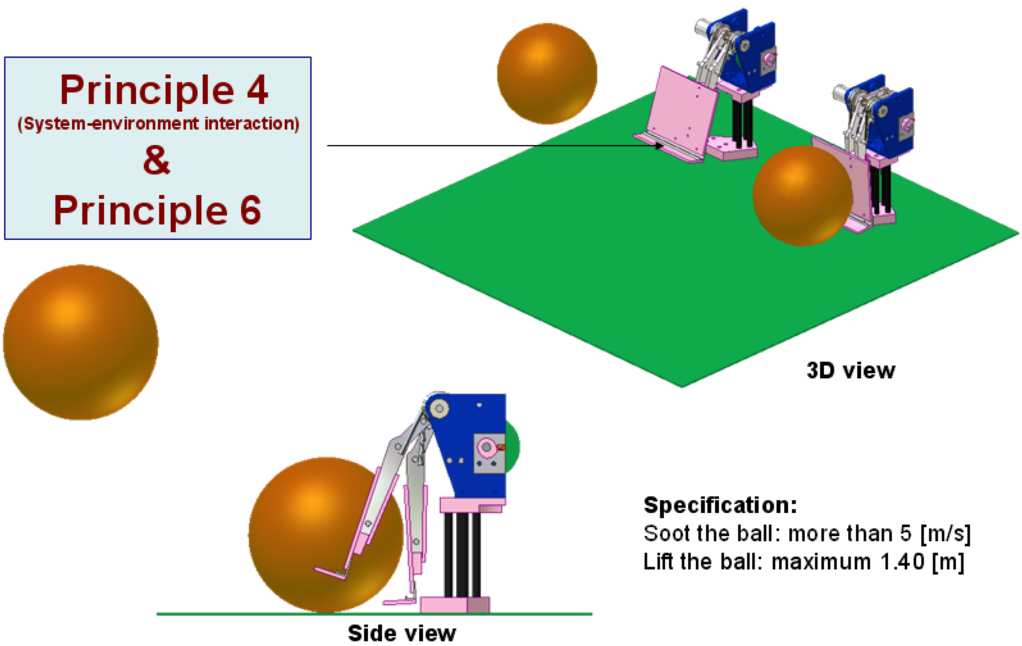


Figure 3.31: Ball-lifting mechanism.

mechanism to hold the ball (*Applying the principle 6*). This linkage mechanism is activated and controlled by the same motor and limit switch used for lifting the ball as shown in Fig. 3.33. The key point is using the death area used for lucking the "Cam Charger" mechanism. In lucking area, if the motor is rotating the kicking plate does not move but the linkage mechanism will be active by pushing the small cam fixed to the big cam.

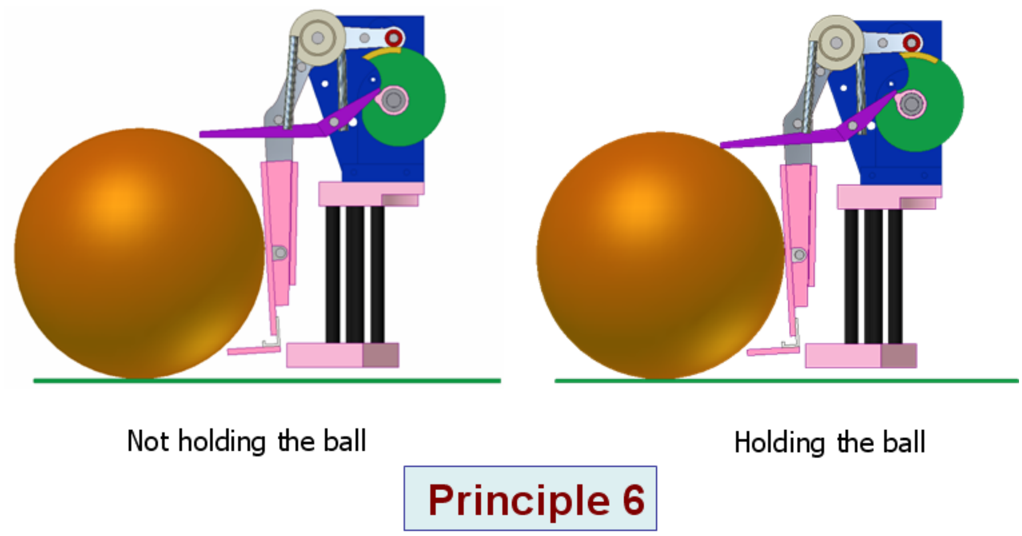


Figure 3.32: Ball-holding mechanism.

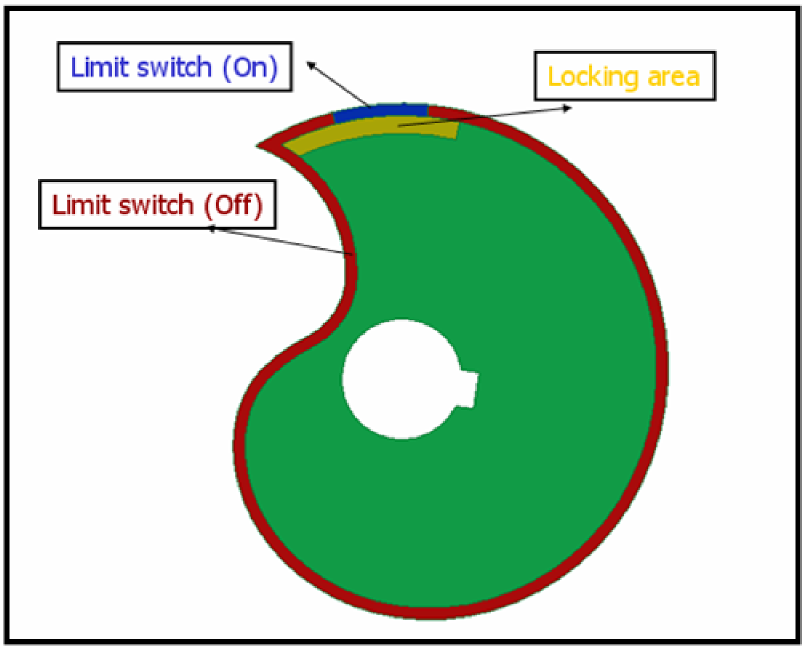


Figure 3.33: Control sequences of the ball-lifting mechanism.

3.6 Conclusion and Experimental Result

In this chapter we presented an autonomous mobile soccer robot which has a fully mechatronics modular architecture including a strong ball-kicking device with capability of lifting the ball and a ball-holding mechanism, aiming at getting champion in RoboCup Mid size League. We proposed a mechatronics modular platform consists of an omni-directional moving mechanism, an omni-vision and a novel ball-kicking-lifting-holding device. In this approach we show that selecting a proper mechanical moving mechanism and a suitable vision system can lead to realize a reliable, simple, and low cost robot comparing with the first version of our car-like soccer robot included many different kinds of sensors and a complex design structure. We described, in detail, the design and developing process of a strong kicking device with capability of shooting (up to 5 [m/s]), lifting (up to 120 [cm]), and holding the ball. The ball-kicking is accomplished by design of an unique spring charging mechanism called "Cam Charger". The key idea is to charge a series of strong torsion springs by using a special design of a cam shape. One of the specific features of the Cam Charger mechanism, is that, charging, keeping and releasing of the springs energy are done only employ a simple DC motor-gearhead and a limit switch. Another special point is that the design of the kicking mechanism can be extended to hold the ball by adding a simple linkage mechanism to the Cam Charger structure. The same motor and the limit switch, used for the ball-kicking, employed to activate and control the linkage mechanism of ball-holding.

This kicking device, also, has an inherent design characteristic to lift the ball by using the different shape of plates installed on the kicker. As a result, Hibikino-Musashi got the first place at RoboCup Japan Open 2006 and was ranked among the best 8 teams at the RoboCup 2006 world championships in Bremen.

Chapter 4
Artistic Robot

Chapter 4

Artistic Robot

4.1 Introduction

Human beings and animals have remarkable abilities to walk, run and jump over a wide variety of hazard terrains. These actions in general are dynamic activities in which inertial forces are significant and balance is achieved by dynamic responses. There have been a number of efforts to build robots with running and jumping capability. An early jumping robot was Matsuoka's planar one-legged hopper in 1980 that had short stance time with thrust provided by a high-force electric solenoid.[3] Marc Raibert developed one-, two-, and four-leg that can balance in the plane and in 3D in the 1980s [12, 13]. These robots had telescoping legs with internal air spring for compliance, and hydraulic actuators. More recently, the Jet Propulsion Laboratory developed a several jumping robots [14] and Sandia National Laboratories created a robot capable of jumping thousands of times [15]. S.A. Stoeter and N. Papanikolopoulos proposed a small cylindrical robot, Scout, capable of rolling and jumping [16, 17]. "Jumping Joe"s are artistic and agile robots that perform acrobatic movements such as fast wake up, jumping and somersault. The main objective of these robots are the development of new behavior like jumping, rolling and their combinations. The full function Jumping Joe design is shown in Fig.4.1. In order to realize acrobatic movements, like rapid getting-up, walking, jumping and somersault, four kinds of actuators which have been designed to create high-speed movements are installed. Inertia actuator, installed in the upper body, is a torque generator that consists of a rotor and a brake mechanism. Each of hip joints consists of a 2 DOF actuator developed on a basis of parallel link mechanisms for achieving light weight and high torque. The knee joints have 1 DOF, high torque mechanisms employing a lever-crank mechanism. Each jumping foot has 1 DOF and is designed based on a special mechanism named "Cam Charger" consists of a special designed cam and torsion springs. Each actuator is developed as an independent module, with the movements being controlled by microcomputer PICs. The central

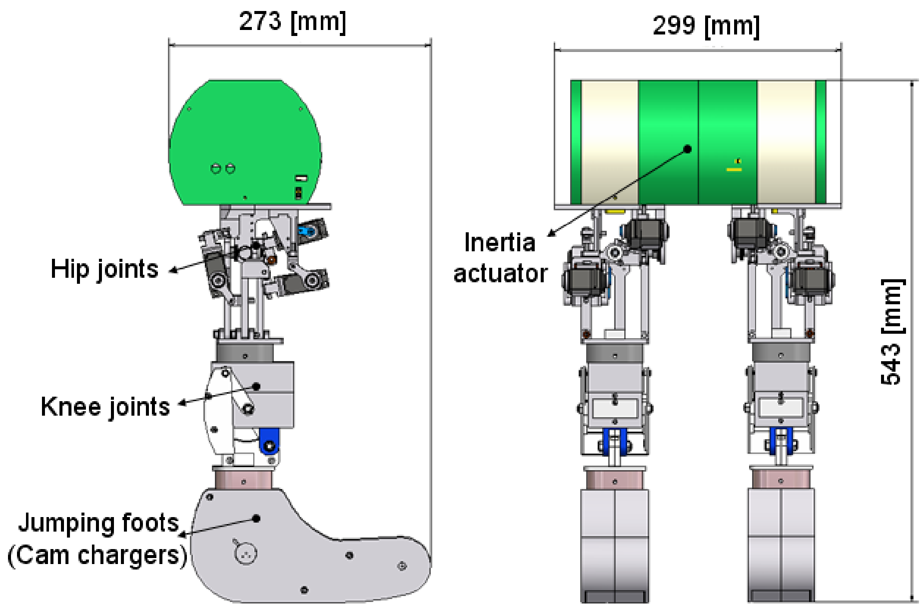


Figure 4.1: Design of full function Jumping Joe. Full function Jumping Joe has eight degrees of freedom, two DOF in each hip joint and one DOF in each knee joint and each foot.

IC is a rewritable FPGA that controls each microcomputer and communicates wireless with a host computer via Bluetooth.

4.2 Mecha-telligence methodology

In this section the mecha-telligence methodology will be described for design and implementation of an artistic robot.

4.2.1 Description of the basic terms

The aim of this project was to exhibit an artistic robot in Aichi Exposition 2005. We proposed a proposal to the NEDO (New Energy and Industrial Technology Development Organization) for design, simulation and implementation of a legged robot with no hand that it can perform the rapid movements such as fast wake up, jumping, and somersault.

Robot task

By considering the aim of what we would like to exhibit, *"Artistic actions"* can be recognized as the robot's task.

Desired behavior

Based on the presented proposal the desired behavior can be described in two following sentences:

- The artistic robot is standing or laying down on a flat surface.
- The robot, suddenly, performs different rapid movements such as fast wake up, jumping, and somersault.

Environmental niche and relative constraints

Alternatively, regard to the presented proposal and exhibition area, the environmental niche and the relative constraints can be defined and itemized as follows: (Fig. 4.2) Environmental niche:

- Indoor environment (Direct-physical meaning)
- A flat surface (Direct-physical meaning)

Environmental niche constraint:

- Robot has two leg (Indirect-physical meaning)
- Robot has no hand (Indirect-physical meaning)

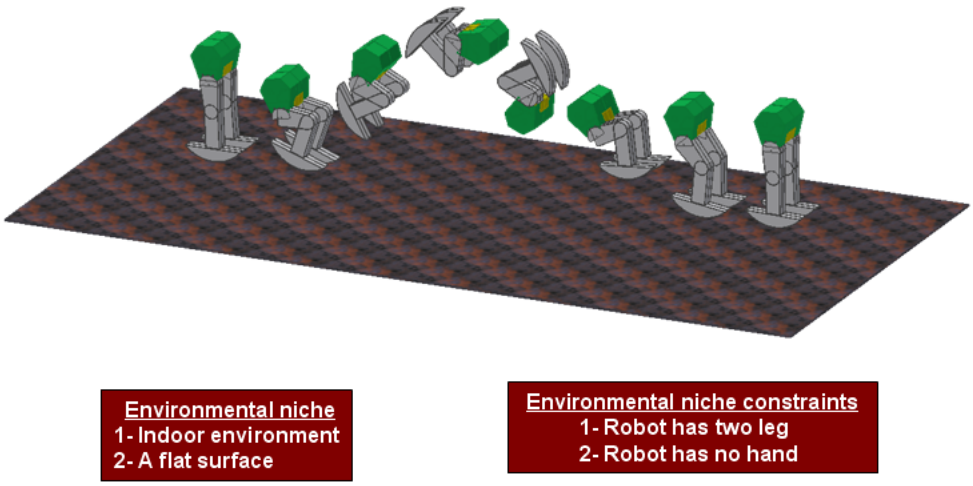


Figure 4.2: The definitions of environmental niche and the relative constraints (Artistic robot).

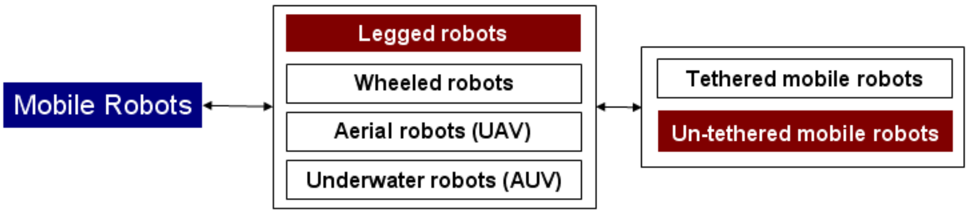


Figure 4.3: The selected type of artistic robot.

Degree of autonomy and mobility

Robot should perform all actions, completely, autonomously without human intermediary. Only the start, stop, and desired actions can be sent via wireless communication to the robot by a human operator. Robot has to be designed as a legged type-untethered robot (Fig. 4.3).

4.2.2 Simplification process of design functions

High-level specification layers (Main layer and Sub layer)

Regard to the description of four above terms, the high-level specification layers including main-layer and sub-layer can be illustrated as Fig. 4.4.

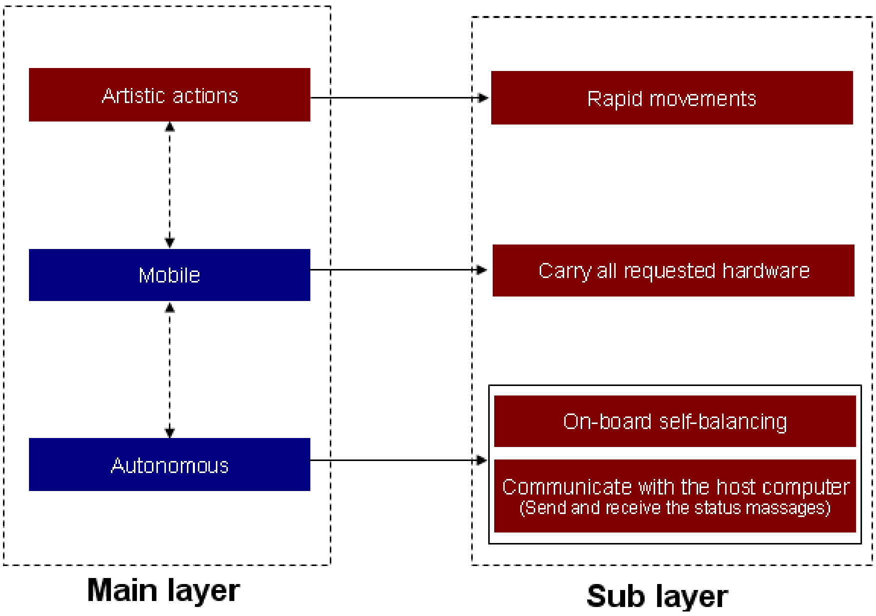


Figure 4.4: The high-level specification layers including main-layer and sub-layer (Artistic robot).

Low-level specification layers (Layer 1, layer 2, and mono-spec layer)

Figures 4.5 and 4.6 show the generation of layer 1 and mono-spec layer, respectively. In this three figures the red color shows the terms which are on the process of simplification, white color illustrates the terms that are not important for our design purpose, and yellow color indicates the terms which recognized as a simple basic function or selecting a sensor for a single task or behavior.

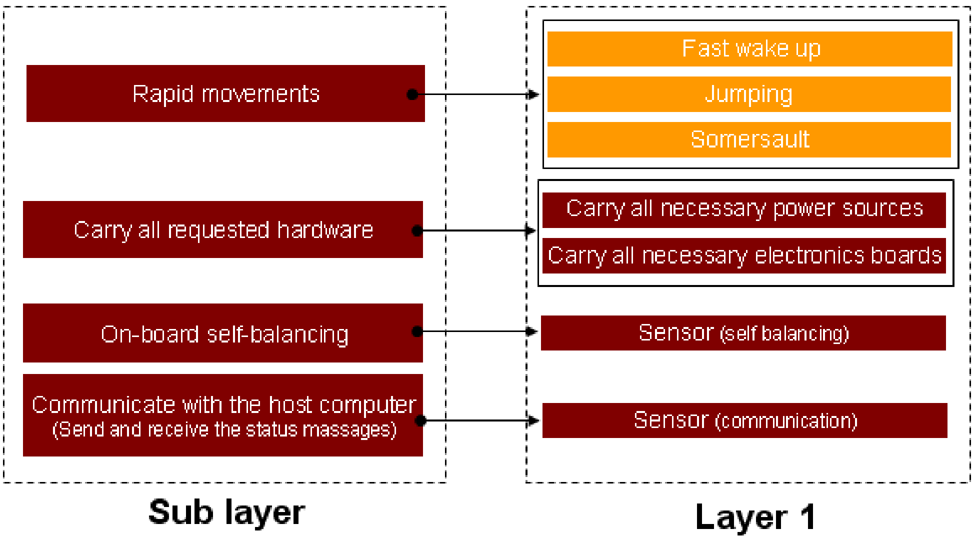


Figure 4.5: The layer 1 generated from the sub-layer (Artistic robot).

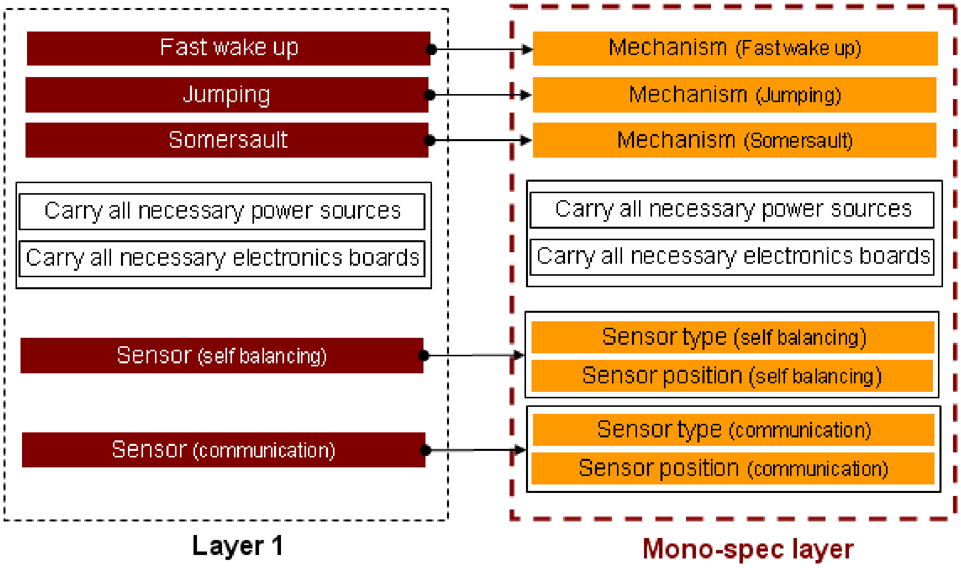


Figure 4.6: The mono-spec layer generated from the layer 1(Artistic robot).

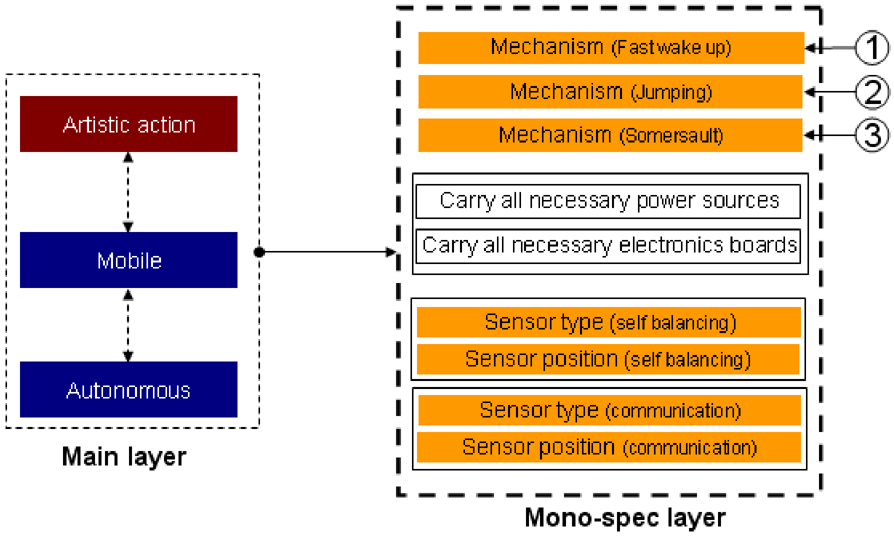


Figure 4.7: Results of the mono-spec layer generation and the function design priority (Artistic robot).

Functions priority of design

Figure 4.7 shows the result of our simplification process from "main layer" to "mono-spec layer". Also, this figure illustrates the function design priority in point of view of mechanical parts design.

4.2.3 Design process: Applying the "Mecha-telligence principle"

This sub-section provides, only, an overview to our robot design and its architecture. Also it shows how the "mecha-telligence principles" have been applied in the process of the design. The whole detail designs and all definition and description of the related concepts are explained in the next sections. To deep understanding about our approach and detail of the robot design, reading the these sections is recommended.

Designing function 1

Realization of the fast wake up can be achieved in two basic ways illustrated in Fig. 4.8. By considering the environmental niche constraint and *applying principle 4*, for a legged robot with no hand the second alternative can be expected. To generate an internal torque, we designed and developed a new type of actuator, called "Inertia actuator" (*Applying principle 5*). Inertia Actuator absorbs mechanical energy by increasing its rotor angular velocity and delivers energy by decreasing its rotor velocity. Inertia Actuator can generate a small internal torque by changing the speed of the rotor and a big internal torque in short time by using a brake to stop the rotor at high speed.

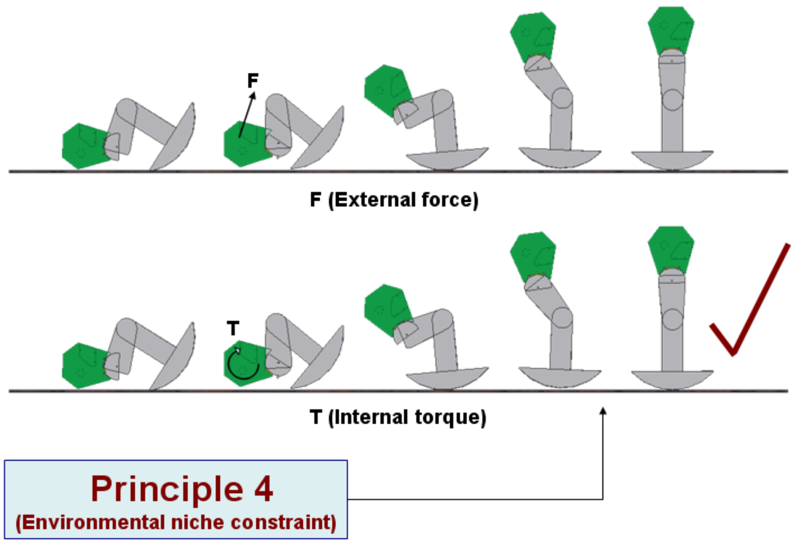


Figure 4.8: Two alternatives for fast wake-up action.

Designing function 2 and 3

In order to realize the jumping capability "Cam Charger" mechanism, presented as a kicking device for RoboCup, is redesigned to fit to the foot shape (*Applying principle 5*). In this case we designed a unique and compact cam including a releasing part to avoid the distribution of the force at the moment of springs energy releasing to the foot structure. The action of somersault is performed by combination of jumping and rotating using "Cam Charger" mechanism and "Inertia Actuator" (*Applying principle 6*).

For easy to follow what we did and what we designed, the results are visualized in Fig. 4.9. The black color shows our solutions for the listed problems, related to the mechanical design, in the mono-spec layer.

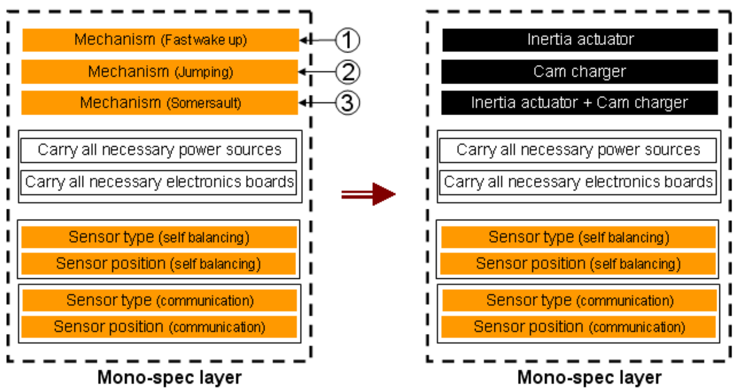


Figure 4.9: The results of design (Artistic robot). The black color shows our solutions for the listed mechanical problems in the mono-spec layer.

4.3 Mechanical Design of "Jumping Joe"s

4.3.1 Inertia Actuator

Inertia Actuator consists of a H-shape cylindrical rotor (maximum diameter : 96 [mm], inner diameter: 75[mm], weight: 1.8[kg]), a DC motor and a brake mechanism (see Fig.4.10) is an inertial energy-storage device. Inertia Actuator absorbs mechanical energy by increasing its rotor angular velocity and delivers energy by decreasing its rotor velocity. In fact, the energy of Inertia Actuator is accumulated as the kinetic energy of the rotor rotation. Inertia Actuator can generate a small internal torque by changing the speed of the rotor and a big internal torque in short time by using a brake to stop the rotor at high speed.[18, 19] The rotor is accelerated up to 6000 [rpm] within 20 [sec], and stopped suddenly using the brake mechanism in approximately 0.15 [sec]. The maximum generated torque is about 12 [Nm] where the moment of inertia of rotor is 3.1×10^{-3} [kg.m^2]. The brake mechanism is designed based on a rim type brake with external contraction shoes, as illustrated in Fig.4.11. The rotor is arranged in the center of the shoe brakes whose diameter including lining (brake material) is almost same with the rotor diameter. When the force F is given to the point P (see Fig.4.12), the force F_C to the point C and F_C to the point D are :

$$F_D = FL_1/L_3 \tag{4.1}$$

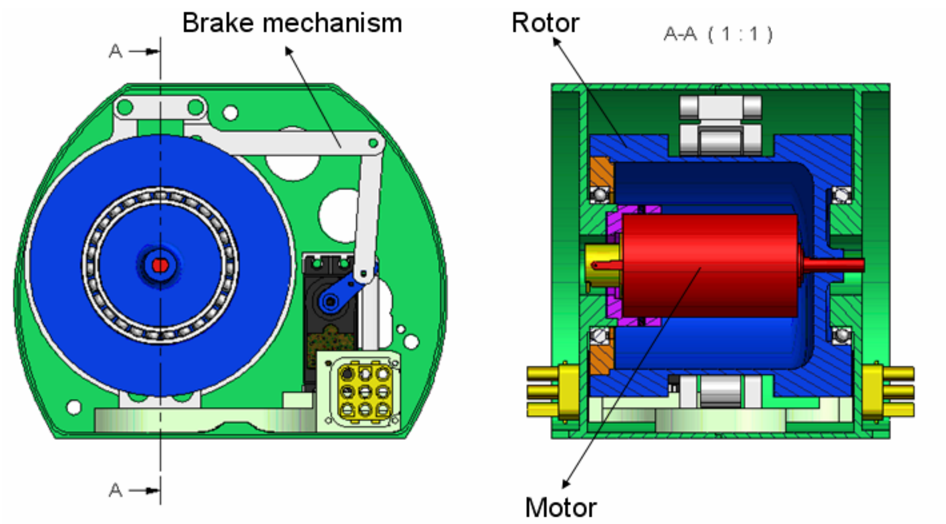


Figure 4.10: Inertia Actuator architecture. Inertia Actuator consists of a H-shape cylindrical rotor and a brake mechanism can generate a small internal torque by changing the speed of the rotor and a big internal torque in short time by using the brake to stop the rotor at high speed.

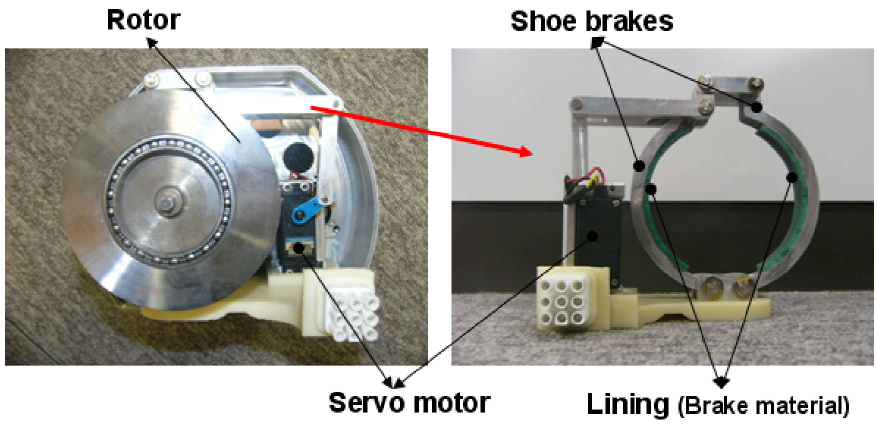


Figure 4.11: The brake mechanism designed based on a rim type brake with external contraction shoes. It stops the Inertia Actuator rotor, accelerated up to 6000 [rpm], in approximately 0.15 [sec].

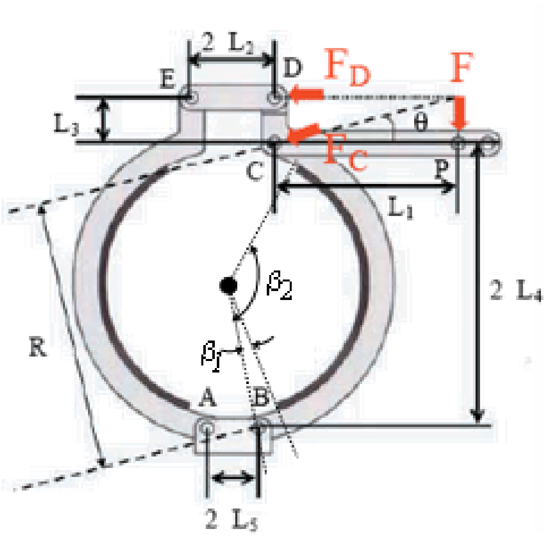


Figure 4.12: Necessary geometric parameters of the brake mechanism for calculation of the motive force F.

$$F_C = F\sqrt{1 + (L_1/L_3)^2} \tag{4.2}$$

Where, L_i is the length of each link (L_1= 57.1, L_2 = 13.0, L_3 = 14.3, L_4 = 44.8, L_5 = 8.0 [mm]). The length R (= 87.55 [mm]) in Fig.4.12 is given as follows:

$$F_C \cdot R = F_C(L_2 - L_5)sin\theta - 2F_C L_4 cos\theta \tag{4.3}$$

$$R = (L_3(L_2 - L_5) - 2L_1L_4)/\sqrt{L_1^2 + L_3^2} \tag{4.4}$$

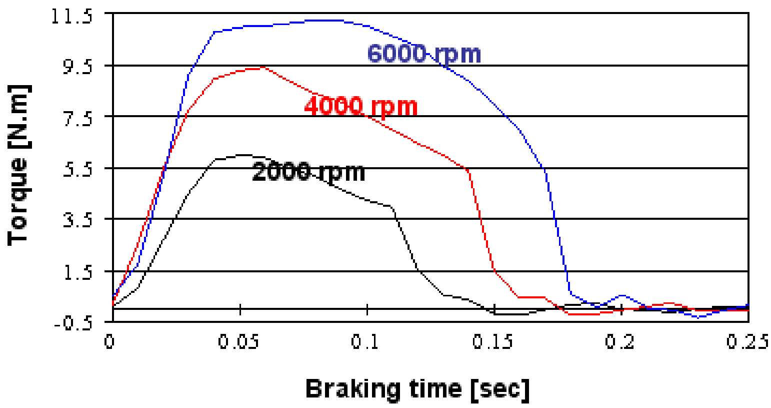


Figure 4.13: The experimental result of the obtained torque from the developed Inertia Actuator. The black line means that the rotor speed is 2000 [rpm], the red line 4000 [rpm] and the blue line 6000 [rpm].

Where, θ is the angle of the force F_C to the link C-P, the relation between the braking force F and braking momentum can be represented in the following equations [20].

$$M_N = \frac{P_a bra}{sin\beta_a} \int_{\beta_3}^{\beta_2} sin\beta(r - a \cdot cos\beta)d\beta \tag{4.5}$$

$$M_f = \frac{f P_a bra}{sin\beta_a} \int_{\beta_3}^{\beta_2} sin^2\beta d\beta \tag{4.6}$$

$$F_C = (M_N - M_f)/R \quad (If\, the\, rotor\, rotates\, clockwise) \tag{4.7}$$

$$F_D = (M_N + M_f)/(2L_4 + L_3) \;\; (If\, the\, rotor\, rotates\, counterclockwise) \tag{4.8}$$

Here, P_a(=542 [kpa]) is the maximum pressure of the brake material, b (=15 [mm]) is the width of the brake material, f (=0.32) is the friction coefficient between the rotor and the brake material , r (=40 [mm]) is the distance between the center of rotor and the brake shoe, a (=46 [mm]) is the distance between the center of rotor and the joint B, and $\beta_a = \beta_2$ if $\beta_2 \leq 90°$otherwise $\beta_2 = 90°$. The lining (brake material) is the "J-2 frictional material" of STARLITE Co.,Ltd.. having a coefficient of friction (f) of 1.8 at 25 [C]. The brake is actuated by a simple linkage mechanism connected to a servo motor, shown in Fig.4.13 with 3 [Nm] torque as a peak. The selected servo motor can create the required force F (=64.55 [N]) calculated in eq.(4.2) where $\beta_1 = 15°$ and $\beta_2 = 145°$. The experimental results are shown in Fig.4.14. The rotor in the

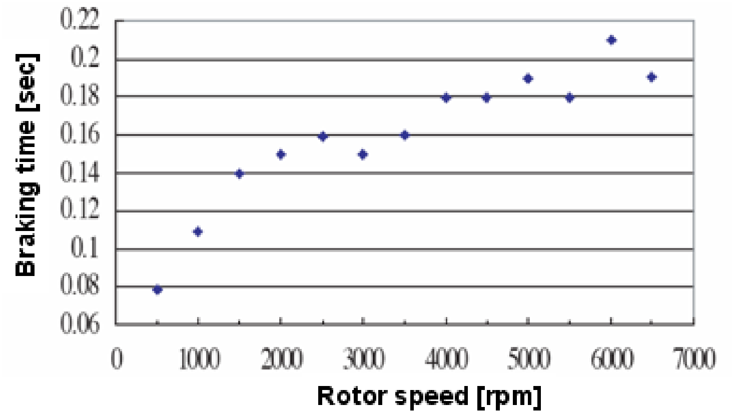


Figure 4.14: This graph shows the braking time for the different rotation speed of the Inertia Actuator rotor.

experiments is a cylinder with the outer diameter: 80 [mm], the inner diameter: 55 [mm], weight: 2.0 [kg] and the inertia moment: 2.3×10^{-3} [kgm^2]). The obtained torque increases according that the rotation speed is going up or the braking time is going down. The maximum torque at 6000 [rpm] is approximately 11.5 [Nm]. The braking time to stop the rotor with different rotation speed is shown in Fig.4.14. At the operation velocity 2000 to 6000 [rpm], it takes between 0.15 and 0.2 [sec]. The Inertia Actuator can generate big torque in a short time and the gyro effect to keep the robot stable is also expected.

4.3.2 Hip Joint

A robot which performs acrobatic behaviors such as jump, waking-up, somersault, etc., needs very powerful , quick and small actuators. In this research, we utilized a parallel mechanism [21] to the hip joints. The parallel mechanism can distribute external forces given to the end-effector into each link and all output forces from all active joints are synthesized and become an output of the end-effector. The output torque of parallel mechanisms can be increased without a large ratio gear so that, a speedy and powerful motion can be expected. On the other hand, parallel mechanisms has the disadvantages such that the workspace is smaller than that of serial link manipulators, and the kinematics and dynamics are complicated so that the computational power is needed in order to solve these equations of motion in real-time. Most of applications of the parallel mechanism into walking robots employ planar mechanisms such as pantograph mechanism. Recently, the parallel mechanism with special movements is also applied as the actuators of walking robots. Para-walker developed by Ota et. al. [22], has the serial/parallel hybrid mechanism to climb over hazardous terrain, and WL_16 de-

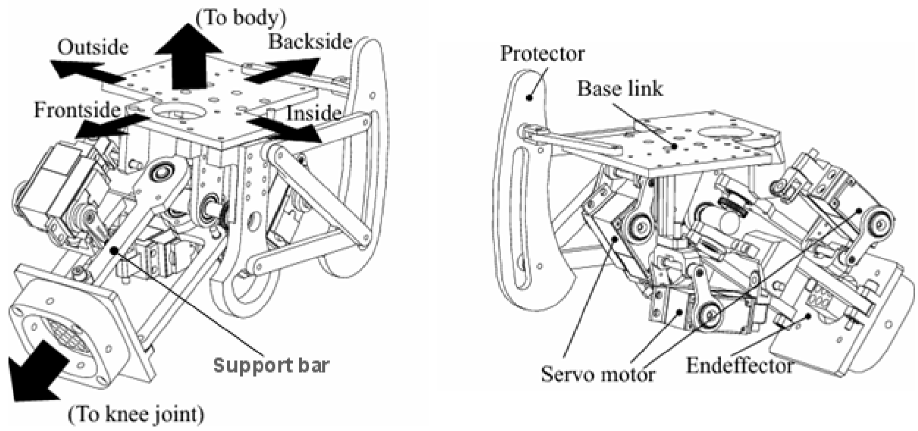


Figure 4.15: The developed 2 DOF hip joint. Each arm has a servo motor in the middle joint and the motion is restricted by the support bar in the center.

veloped by Sugawara et. al., is a biped robot on which an operator can get on. The parallel mechanism of Steward platform is introduced into each leg [23].

The developed hip joint (See Fig. 4.15) consists of a base link, 3 serial-link arms, 3 servo motors (3 [Nm]), an end effector and a protector. Each arm is composed of 5 passive joints and 1 active joint as shown in Fig. 4.16. In the most applications, the active joint is arranged at the end of serial-link arm. One of the specific feature of the developed hip join is that the active joint locates in the middle of serial-link arm in order to keep a larger workspace. The another special point is that the motion of hip joint is restricted to 2 DOF motion, pitching and rolling motion by the support bar in the center of hip joint in spite that the number of motors is 3 (Fig. 4.15). The hip joint can output 10 [Nm] at maximum, and the ranges of pitching and rolling

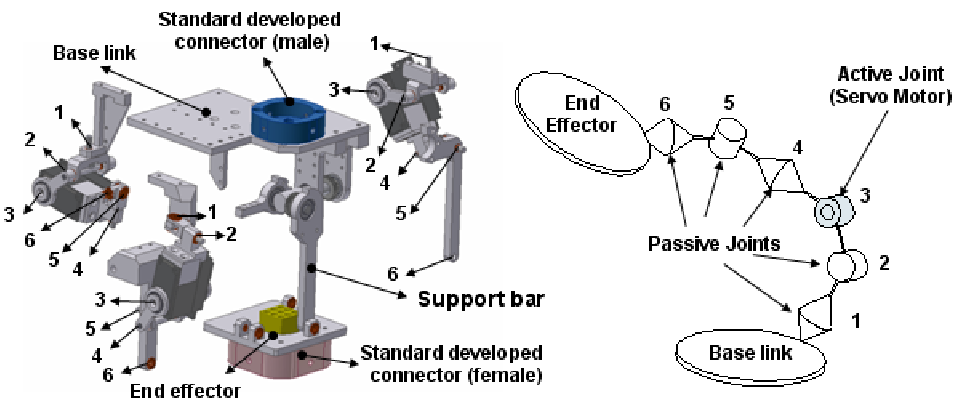


Figure 4.16: The developed hip joint consists of 3 serial-link arms, and the each arm composes of five passive free joints (joint 1,2,4 and 5) and one active joint (joint 3).

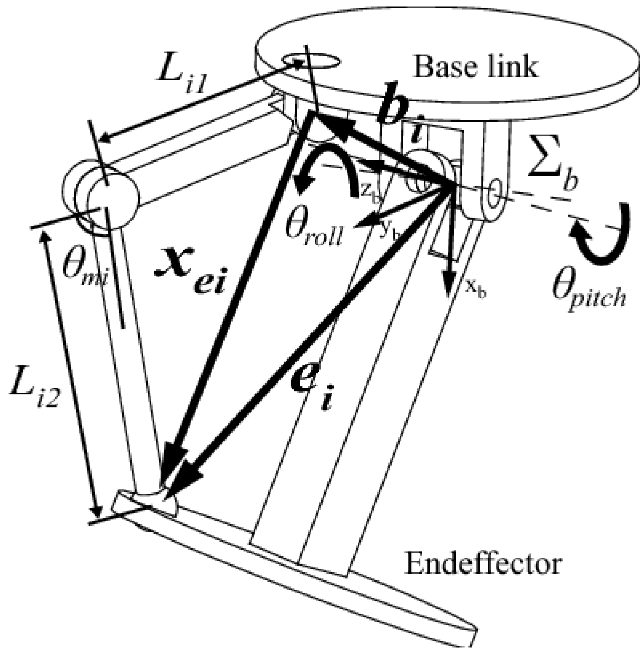


Figure 4.17: The coordinate system and parameters of developed hip joint.The developed 2 DOF hip joint.

angles are 110 [deg] and 45 [deg] and the weight is 850 [g]. The parallel mechanism has characteristic singular point [21, 24]. If the posture is in the singular point, it'll become uncontrollable and becomes freely movable at specific directions. The developed hip joint has no singular point within its working space.

The dynamics and kinematics of parallel mechanism are complex because of a lot of active and passive joints, however, inverse kinematics can be solved easily for some cases. Figure 4.17 shows the coordinate system and parameters of the developed parallel mechanism. The coordinate systems of the base link and the end-effector are denoted by $\sum_b$ and $\sum_e$, respectively. The attitude angle of the end-effector in $\sum_b$ is given by $\theta_{\mathbf{e}} = [0, \theta_{ey}, \theta_{ez}]^T$, where the angle along x axis is zero because the the rotation around x-axis is restricted by the support bar. Let the position of the joint on the end-effector J_{i3} (i: index of arm) in $\sum_e$ is ${}^{\mathbf{e}}\mathbf{e_i} = [{}^e e_{ix}, {}^e e_{iy}, {}^e e_{iz}]^T$, and the position of the joint on the base link J_{i1} in $\sum_b$ is $\mathbf{b_i} = [b_{ix}, b_{iy}, b_{iz}]^T$, respectively. The vector from J_{i1} to J_{i3}, $\mathbf{x_{ei}} = [x_{eix}, x_{eiy}, x_{eiz}]^T$ in $\sum_b$ is expressed by eq. (4.9).

$$\mathbf{x_{ei}} = {}^B R_E {}^{\mathbf{e}}\mathbf{e_i} - \mathbf{b_i} \tag{4.9}$$

The rotation angle θ_{i3} is expressed by following eq. (4.10).

$$\theta_{i3} = \pm acos(\frac{\mid x_{ei} \mid^2 - \mid x_{i1} \mid^2 - \mid x_{i2} \mid^2}{2 \mid x_{i1} \mid\mid x_{i2} \mid}) \tag{4.10}$$

4.3.3 Knee Joint

The knee joint is designed using Lever-Crank mechanism. The required range of motion is 110 [deg] where the rotation angle of input joint is 180 [deg], and the required torque is more than 8 [Nm] which is 1.3 times larger than input torque 6 [Nm]. Figure 4.18 shows the geometric parameters of Lever-Crank mechanism. The input joint is the point A and the output is D. By the way of Shirakawa's triangular method, the relations of angles and torques between A and D can be obtained with following equations. Where the input angle is α , the length of BD is given as:

$$l_5^2 = l_1^2 + l_4^2 - 2l_1l_4cos\alpha \tag{4.11}$$

then, the angle δ is:

$$\varepsilon = cos^{-1}(\frac{l_4^2 + l_5^2 - l_1^2}{2l_4l_5}) \tag{4.12}$$

$$\zeta = cos^{-1}(\frac{l_3^2 + l_5^2 - l_2^2}{2l_3l_5}) \tag{4.13}$$

$$\delta = \varepsilon + \zeta \tag{4.14}$$

Where the input torqueT_a is given, the output torque T_d can be calculated as follows [25]:

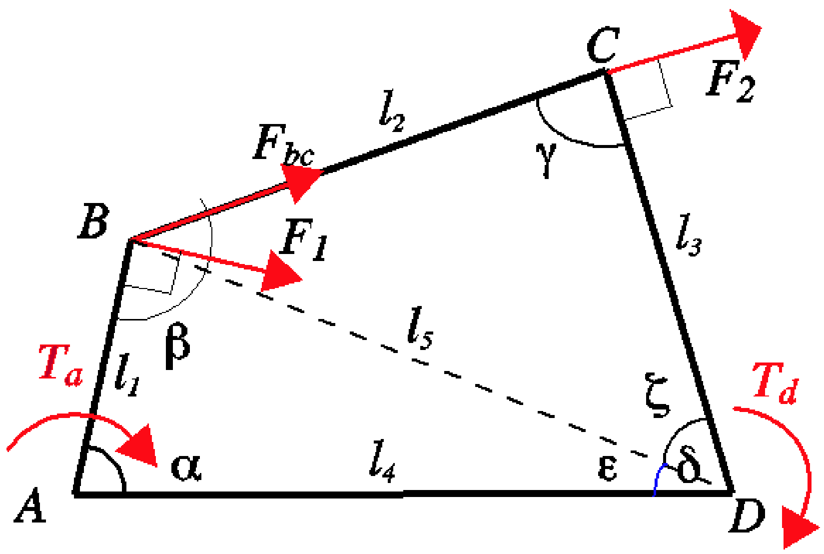


Figure 4.18: The necessary geometric parameters of Lever-rank mechanism.

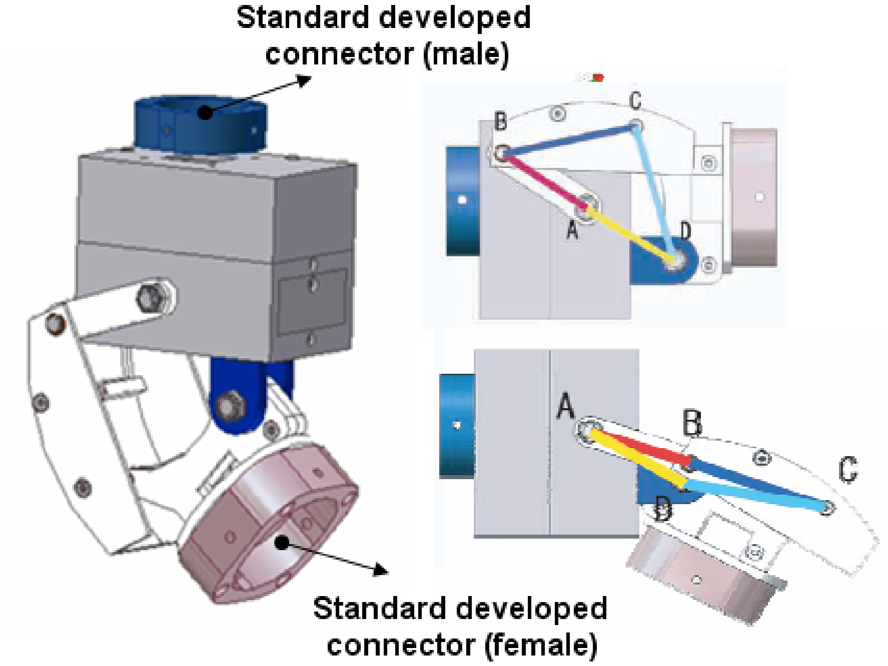


Figure 4.19: The developed knee joint using lever-crank mechanism. The points A, B,C, and D correspond to those points of fig. 4.18. The joint angle is set to 0 in the right-top figure, and approximately 110 degree in the right-bottom.

$$F_1 = T_a/l_1 \tag{4.15}$$

$$F_{bc} = F_1/sin\beta \tag{4.16}$$

$$F_2 = F_{bc}sin\gamma \tag{4.17}$$

$$T_d = F_2 l_4 = \frac{l_4 sin\gamma}{l_1 sin\beta} \cdot T_a \tag{4.18}$$

Where, the each length of links l_i is selected as 27[mm], 40 [mm], 40 [mm] and 30 [mm], respectively. The overview of the developed knee joint is illustrated in Fig. 4.19. The points A to D correspond to the those points of Fig. 4.18 and the joint angle δ is set to 0 [deg] in the right-top and approximately 110 [deg] in the right-bottom of Fig 4.19. The relation between the angle δ and the torque T_d is shown in Fig. 4.20. The knee joint takes a minimum torque 8.1 [Nm] where the angle δ is about 70 to 80 [deg].

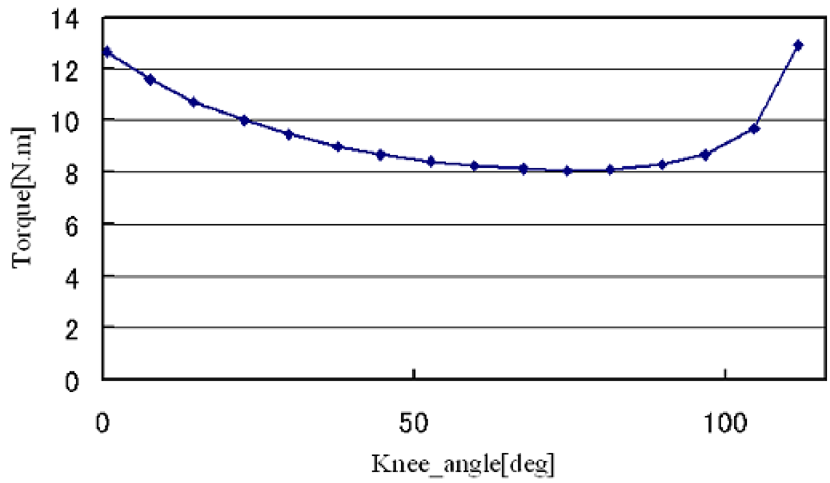


Figure 4.20: The relation between the angle of knee joint and the obtained torque. The input torque and range of knee joint angle are 6 [Nm] and 180 [deg], respectively.

4.3.4 Jumping Foot

In order to realize the jumping capability, Cam Charger mechanism [26] is introduced to fit to the foot shape. The key idea is to charge a series of strong torsion spring by using a special design of a cam shape. The basic concept of this mechanism is shown in Fig. 4.21. With regard to the eqs. (4.19) and (4.20), the motive force (F) to charge the torsion spring is minimized while the force (F) is perpendicular to the axes (m) (β =90°) where the torque τ_S takes a certain value.

$$F = \frac{\tau_S}{X \cdot sin\beta} \tag{4.19}$$

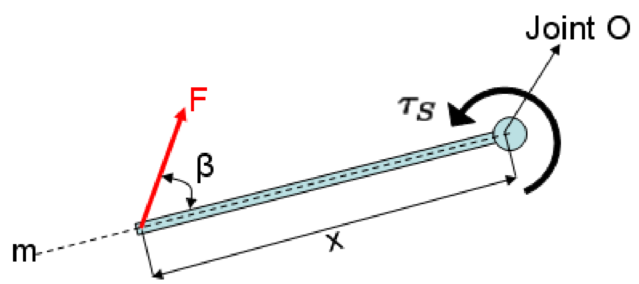


Figure 4.21: Basic concept of cam charger mechanism. Joint A is fixed and the springs, as a resistance torque, are mounted in this joint. τ_S = spring torque (resistant torque), F= Motive force, X= distance between joint (O) and the point where force (F) is applied, β = angle between force (F) and the direction of (m).

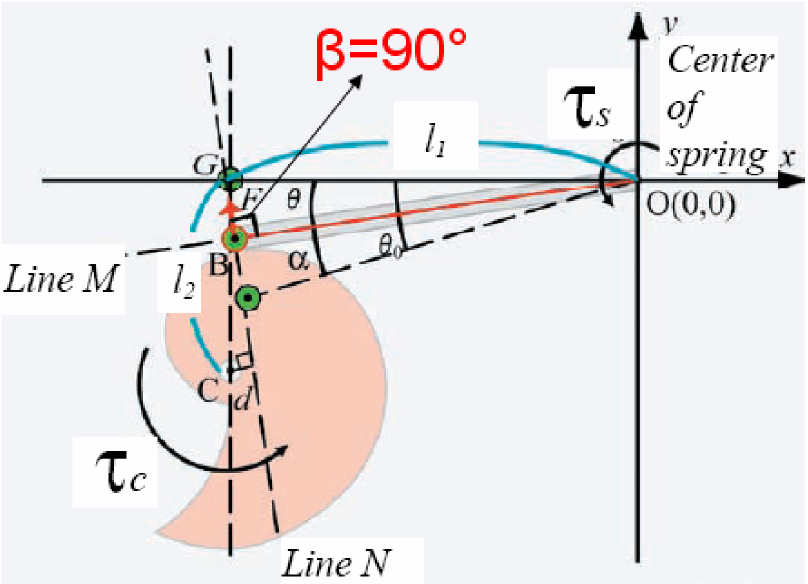


Figure 4.22: The coordinate and relation between the cam and the torsion spring. The main function of the cam is keeping the β angle 90 degree in during the spring charging process.

$$\beta = 90^{\circ} \Longrightarrow F_{min} = \frac{\tau_S}{X} \tag{4.20}$$

The main function of the special designed cam is keeping the angle β 90° during the spring charging process (Fig. 4.22). Then the torque of motor τ_C, needed to charge the spring, will be minimized as following equation:

$$\tau_{C\,(min)} = F_{min} \cdot d \tag{4.21}$$

where d is the perpendicular distance between the direction of contact force F (line N) and the center of the cam C. The distance d can be calculated with the following equations:

$$Line\,M:\;\; y = x \cdot tan\theta \tag{4.22}$$

$$Line\,N:\;\; x \cdot cos\theta + y \cdot sin\theta + l_1 = 0 \tag{4.23}$$

$$d = \frac{-l_1 cos\theta - l_2 sin\theta + l_1}{\sqrt{cos^2\theta + sin^2\theta}} = -l_1 cos\theta - l_2 sin\theta + l_1 \tag{4.24}$$

Here, l_1 is the length of OG, and the angle θ is the angle between the line OG and the line M. And the force F and τ_C can be obtained as following:

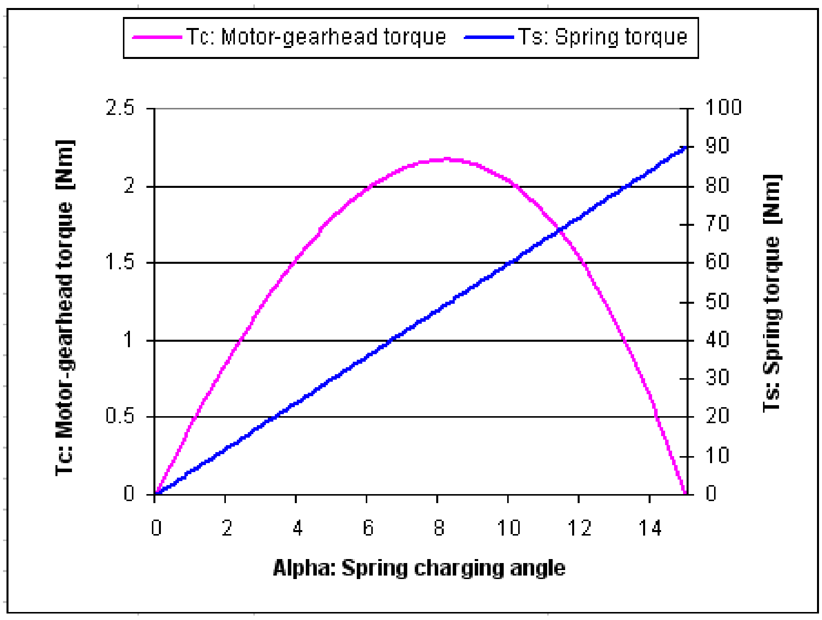


Figure 4.23: The derivation of motor torque τ_C (red graph) and spring torque (blue graph) respect to the charged angle of spring α where $n=2$, k=3.0 [Nm/deg], α = maximum 15 [deg], l_1=150 [mm] and l_2=64.7[mm].

$$F = \frac{\tau_S}{l_1} = \frac{nk\alpha}{l_1} \tag{4.25}$$

$$\tau_C = F \cdot d = nk\alpha(1 - cos\theta - l_2 sin\theta / l_1) \tag{4.26}$$

Where n is the number of springs, k is the stiffness coefficient of springs and α is the charging angle of springs. In this mechanism, during the charging time, the perpendicular distance between the direction of contact force F and the center of the cam (d in Fig.4.22) decreases when the spring torque (τ_S) and the contact force (F) increase. The red line in Fig.4.23 shows the derivation of motor torque relative to the charged angle of springs. The important point is that when the spring is charged more and more, the required motor torque is getting less and less in the second half of the graph in Fig.4.23. This mechanism makes charging very strong series of torsion springs possible with a small motor. As an example in case of a cam charger with specification $n=2$, k=3.0 [Nm/deg], α = maximum 15 [deg], l_1=150 [mm] and l_2=64.7[mm], for charging the 90 [N.m] resistance torque of two springs, we only need a motor-gearhead which can produce almost 2.2 [N.m] torque as a peak.

In order to realize the jumping capability, the cam charger mechanism is designed so as to fit to the foot shape. The developed jumping foot, illustrated in Fig. 4.24, consists of (1) two torsion spring, (2)a special designed cam, (3)a needle bearing, (4)a releasing

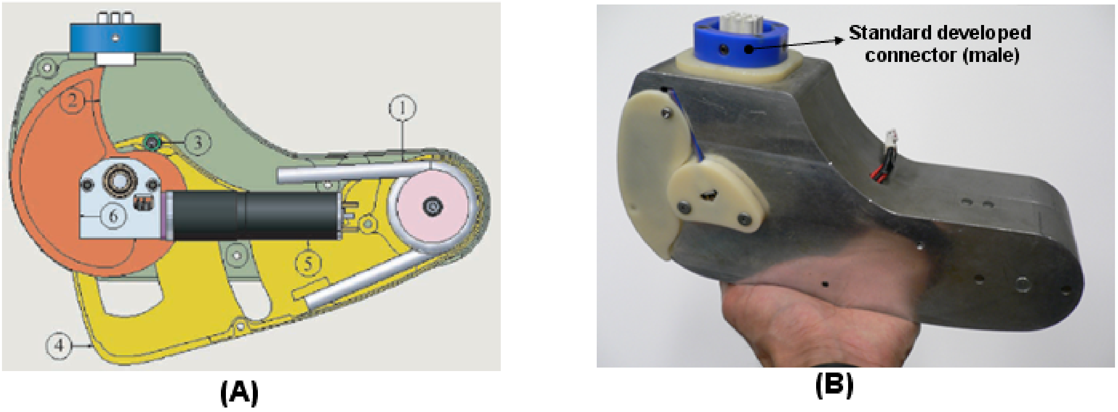


Figure 4.24: (A): To realize the jumping capability, Cam Charger mechanism was designed to fit to the foot shape: (1)torsion spring(s), (2)special designed cam, (3)needle bearing, (4)releasing part, (5) motor and (6) worm gear box. (B): This figure illustrates the developed jumping foot with capability of jumping.

part, (5)a motor and (6)a worm gear box.The cam is designed as the combination of successive circular arc as shown in Fig.4.25-A by using 3D CAD software Auto-desk Inventor. Figure 4.25-B shows the final design of cam where $\alpha = 15$ [deg], l_1=150 [mm], and l_2=64.7[mm]. As mentioned in above, τ_c takes the maximum value around middle of charging angle and becomes 0 at the end of charging, because the direction of F is toward the center of cam and d is 0. The diameter of needle bearing is 9 [mm] and the maximum radius of cam is 60.2 [mm] in the case that the l_1 is set to 150 [mm]. In this case, Cam Charger can charge approximately 41 times strength torsion spring of the maximum torque of the motor. The experimental results of the developed Cam Charger are shown in Fig.4.26. A Cam Charger can make the 5 [kg] weight (including

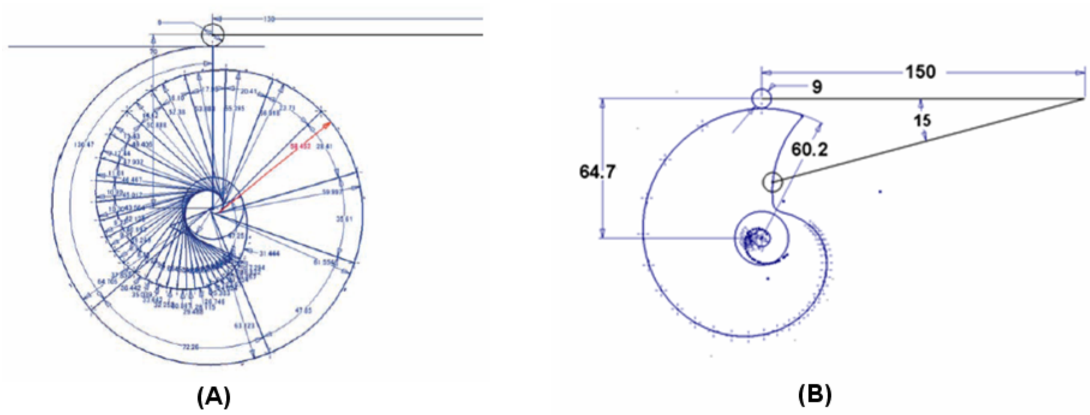


Figure 4.25: (A): The cam is designed as the combination of successive circular arc by using Auto-desk Inventor software. (B): The cam is finalized where $\alpha = 15$ [deg], l_1=150 [mm], and l_2=64.7[mm].

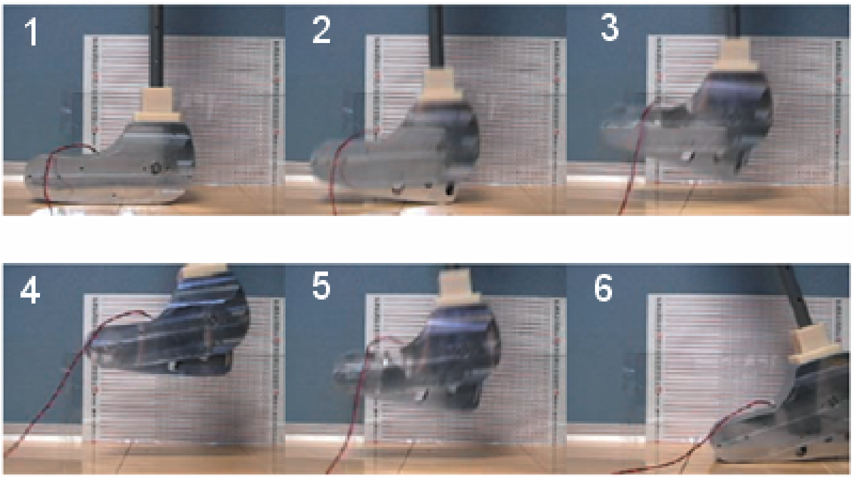


Figure 4.26: The experimental results of the Cam Charger jumping. The Cam Charger can make the 5 [kg] weight (including own weight) jump up to approximately 200 [mm] height.

own weight) jump up to approximately 200 [mm] height. The required jump capability that we assumed is 200 [mm] where the weight of robot is 10 [kg], therefore, the developed Cam Charger suffices the requirement if the two Cam Charger can work at the same moment.

4.4 Electric Circuit Design

4.4.1 Total System Architecture

The system architecture of the full function Jumping Joe is illustrated in Fig.4.27. The commands from the host PC are transmitted by RS232 serial communication, and converted to the Bluetooth wireless communication with "Bluestick"s. We adopted the Bluetooth device because that is small and easy to use within the range of 10 [m]. The host command is sent to the FPGA board through a PIC, and then, the FPGA sends the behavior of the robot to the two Master PICs (one for right side and one for left side) and the control board of the Inertia Actuator (Fig.4.27-B). The Master PICs communicate with all PICs of actuators control circuits using the I^2C protocol (Fig.4.27-A). After a behavior is transmitted to all actuator circuit boards, the Master PICs send the trigger command and the robot starts the performance. As a vision system, the silicon retina developed by Yagi et. al. [27] is introduced. The silicon retina recognizes the motion in the front of robot such as up, down, left or right motion, and sends a command to the FPGA board.

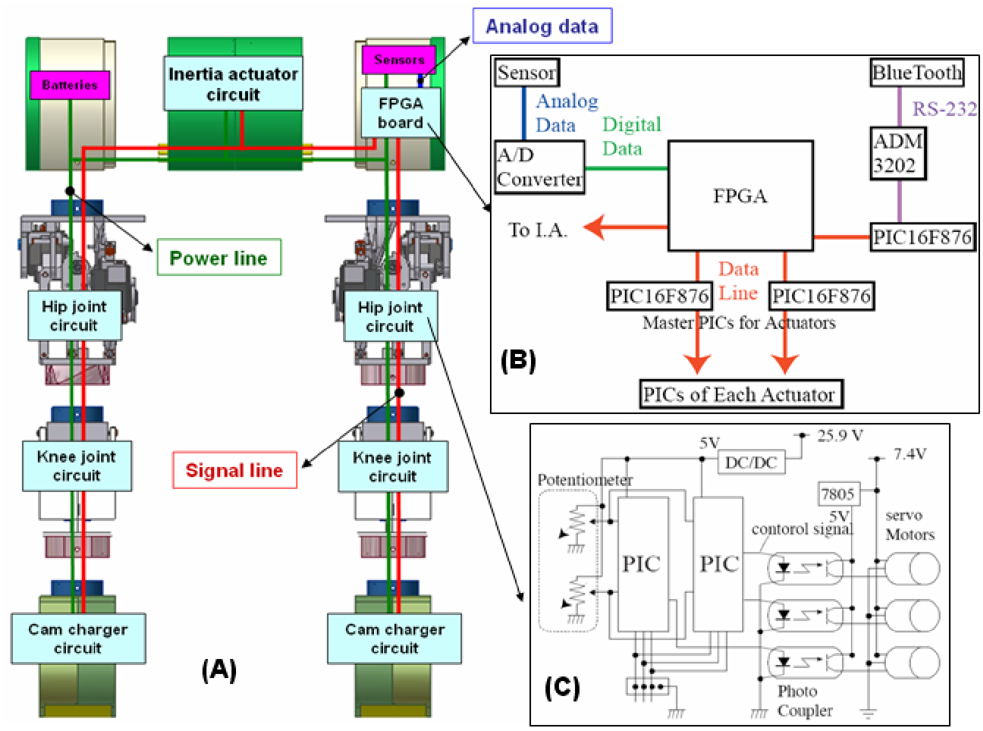


Figure 4.27: Electric system architecture of Jumping Joe. A: Communication between Master PICs and the actuator modules and the power distribution, B: FPGA circuit board and C: Control board of the hip joint.

4.4.2 Control Board of Each Actuator

Each actuator module includes its own microcomputer(s) PIC(s) and communicates with the master PIC via I^2C protocol. As an example, the design of the hip joint control board is shown in Fig.4.27-C. The power source of micro controllers and servo motors are isolated using photo couplers. The servo motors are controlled by PWM signals which correspond to the joint angles. The joint angles are used as the feedback signals. The sampling and control rates are 100 [Hz]. The developed control boards of all actuators are illustrated in Fig.4.28.

4.5 Modular Architecture of "Jumping Joe"s

To achieve the reliability and easy to assemble and maintenance features, "Jumping Joe"s are designed to have a modular architecture in their mechanical parts and eclectic circuits (Applying principle 7: The mechatronic modularity principle). "Jumping Joe"s are made of combination of four main modules: Upper body, Hip joint, Knee joint and Jumping foot. All modules can be plugged to each other via a standard male/female

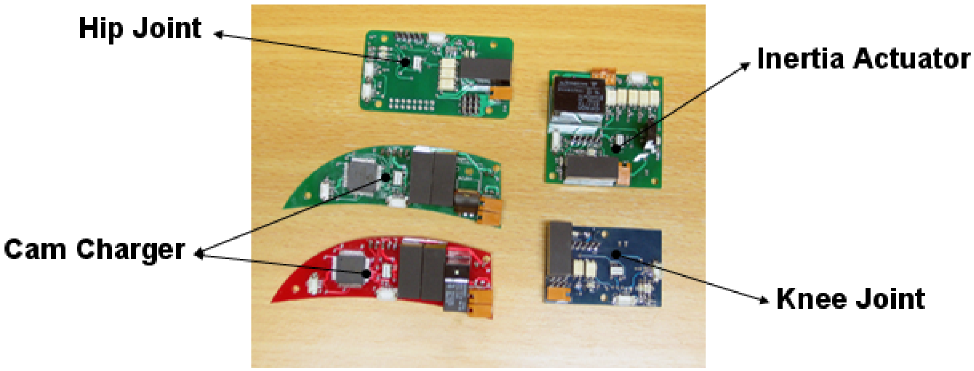


Figure 4.28: The developed control boards of Inertia Actuator, Hip joint, Knee joint and Cam Charger.

developed connector, as showed in Figs. 4.16, 4.19 and 4.24-B, which is designed to work as a mechanical joint and also an electric joint to transmit the power and data. By using the modular architecture for "Jumping Joe"s we can realize the different kinds of artistic robots, only, by plugging the different modules to each others (see Fig.4.29). Upper body module itself divided into 3 modules, which are (a) the battery part located in the left side, (b) the "Inertia Actuator" part in the middle and (c) the electric circuit part in the right side (see Fig.4.30). These three modules can be plugged to each others through their own connectors. Hip joint, Knee joint and Cam Charger modules, as mention in fourth section, include their own microcomputer(s) PIC(s) and

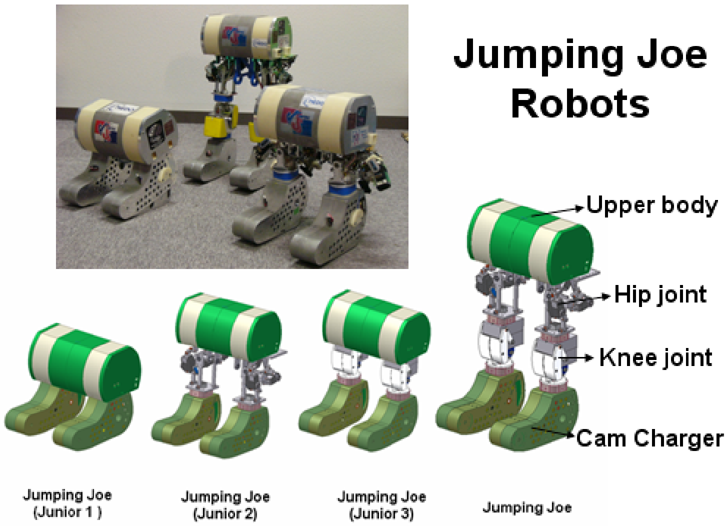


Figure 4.29: By using the modular architecture for "Jumping Joe"s we can realize the different kinds of artistic robots, only, by plugging the different modules to each others. All Jumping Joe robots, at least, consist of a upper body and two cam chargers.

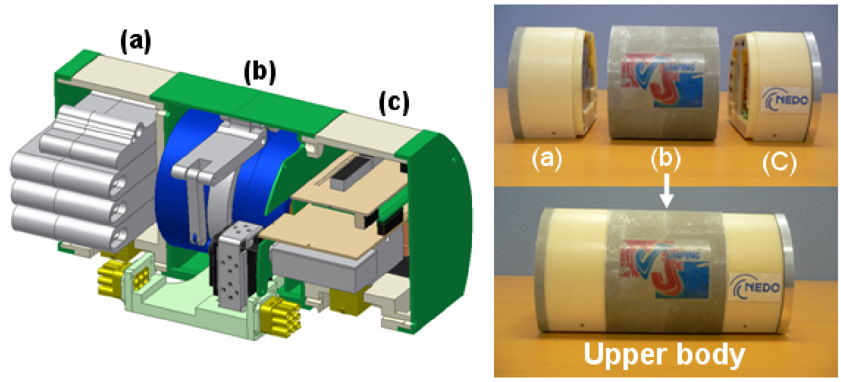


Figure 4.30: Upper body module contains battery part (a), Inertia Actuator part (b), electric circuit part (c) that they plug to each other through their own connector. A standard developed female connector is installed in bottom side of electric part and battery part (not show in the figure).

communicate with the master PIC, located on electric circuit part in the upper body, via I^2C protocol.

4.6 Simulation and Experimental Results

In this section we will show some samples of simulation and experimental results of Jumping Joe robots. Figures 4.31 and 4.32 show the simulation and experimental results of Jumping Joe-Junior 1 during the rapid wake up and somersault action, respectively. For rapid wake up motion, the rotor is rotated up to 6000 [rpm] and stopped suddenly using the brake mechanism in approximately 0.15 [sec]. In case of somersault, the rotor is rotated up to 6000 [rpm] at first, then jumping action is done by Cam Chargers, and after a few milliseconds the brake mechanism stops the rotor suddenly. In the simulation results of the Jumping Joe-Junior 1 during the somer-

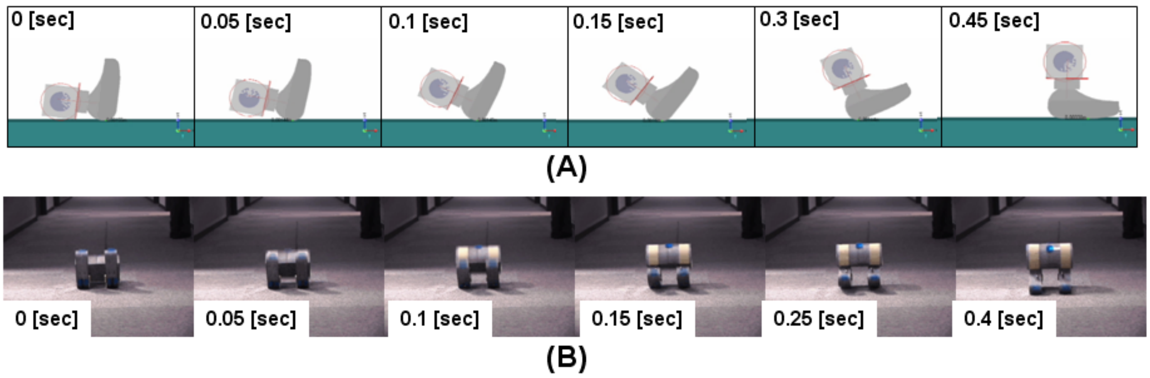


Figure 4.31: Simulation (A: side view) and experimental (B: front view) results of the rapid wake up of Jumping Joe-Junior 1.

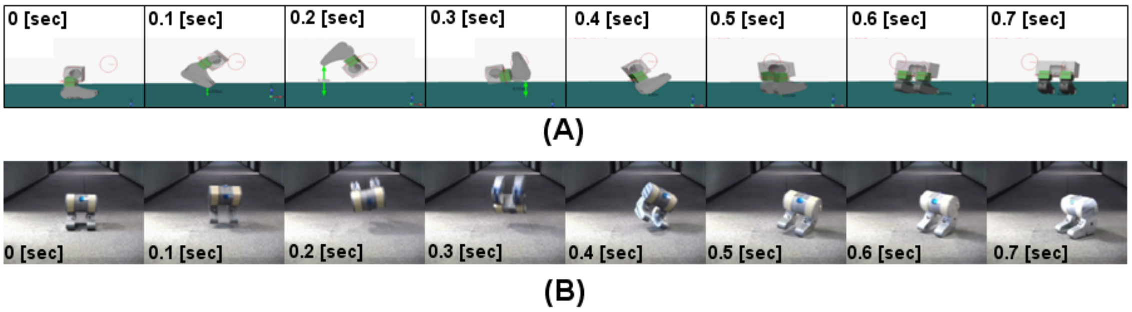


Figure 4.32: Simulation (A: side view) and experimental (B: front view) results of the somersault of Jumping Joe-Junior 1. In the simulation results (A), the robot twisted in the frames at 4.1 sec and 4.2 sec so that it is shown the simulation will correspond with the actual experimental response (B).

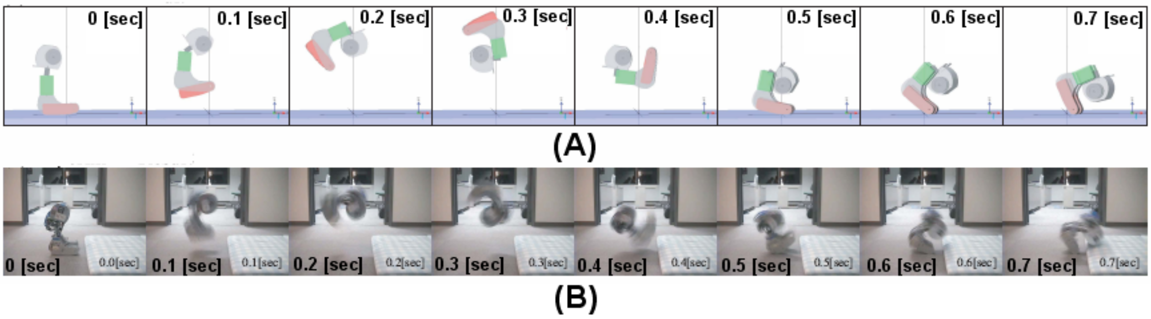


Figure 4.33: Simulation (A: side view) and experimental (B: side view) results of the somersault of Jumping Joe-Junior 2.

sault action (Fig. 4.32_A), the robot twisted in the frames at 4.1 sec and 4.2 sec so that it is shown the simulation will correspond with the actual experimental response (Fig. 4.32_B). The result of somersault simulation and experiment of the Jumping Joe-Junior 2 is illustrated in Fig. 4.33. The hip joint action to make the robot as much as possible close to the circle shape and jumping action is almost done in the same time and after a few millisecond the rotor, which is rotated up to 6000 [rpm] in the beginning, stopped suddenly by the brake mechanism.

4.7 Conclusion

In this chapter, we describe the design, modeling, simulation and implementation of entertainment robots named “Jumping Joe". “Jumping Joe"s, artistic and agile robots, can perform several rapid movements such as fast wake up, jumping and somersault. In order to realize acrobatic movements, four different actuators which can create the high-speed movements are developed. Inertia actuator, installed in the upper body, is a torque generator that consists of Gyro and brake mechanisms. The each of hip joints consists of a 2 DOFF actuator developed on a basis of parallel link mechanisms for achieving light weight and high torque. The knee joints have 1 DOFF, high torque mechanisms employing a lever-crank mechanism. Each jumping foot has 1 DOFF and is designed based on a special mechanism named “Cam Charger " consists of a special designed cam and torsion springs. we still have to perform further experiments and improvements to achieve the proper control method for robot balancing during somersault action. Calculation of the power consumption, required to execute wake-up, jumping and somersault actions is on the future work.

Chapter 5
Sewer Pipe Inspection Robot

Chapter 5

Sewer Pipe Inspection Robot

5.1 Introduction

Major cities invest considerable amounts of budget in underground infrastructure including water and sewage pipes. Many of these pipeline system are prone to damage due to aging, excessive traffic, earthquakes and chemical reaction. Sewage may leak out, possibly polluting soil and ground water, and it may wash away soil, possibly eroding the foundations of buildings or the underground of streets and pavements. The rehabilitation of underground pipes is costly and slow in inspection process. The size of most pipes eliminates the possibility of direct human inspection[1] and requires employment of sophisticated equipment in the process of pipe inspection. With regard to the current sewer pipe inspection technology, all commercial robots are completely tel-operated, usually via a tether cable, by a human operator. In addition, current sewer inspection robots have a poor mobility function to pass any kind of pipe-bends such as curves and junctions so that those robots are only capable to move into the straight pipes. Inspecting the sewage pipes using the state of the arts inspection methods by the current robots is costly, mostly human cost, and not fast enough to check and inspect the amount of sewage pipes will grow stronger than it has actually happened, specially in Japan. In this part of thesis we show our method for realization of an innovative, fast and robust sewer inspection method by using a passive-active intelligent, fully autonomous, UN-tethered robot called "KAN TARO" which fits to the pipes within a diameter range of 200-300 millimeters. KAN TARO prototype robot, including a novel passive-active intelligent moving mechanism (nadir Mechanism), can move into the straight pipe and pass different kinds of pipe bends without need to any intelligence of the controller or sensor reading. In order to realize a fully autonomous

[1] In Japan mostly 85% of the sewer pipes are under 600mm diameter and mainly more than 65% of this amount have a diameter within range of 200-300mm [28]. This is the target diameter of the presented fully autonomous mobile robot “KAN TARO” in this chapter.

inspection robot, we also developed a small and intelligent 2D laser scanner for detecting of the navigational landmarks such as manholes and pipe joints independently with main computer system, and fusion with a fish eye camera to assist the pipe state and fault detection.

5.1.1 State-of-The-Art

In current conventional methods, the inspection of sewer pipes is carried out using a cable-tethered robot with an on-board video camera system. An operator remotely controls the movement of the robot including a video system (Fig. 5.1) and looks for probable damages in the images of the pipe interior. All equipment necessary to supply and control the robot are arranged inside of a car, out of the manhole (definition of manhole has been specified on page 106), which causes a heavy and stiff cable for the robot. In addition, all commercial sewer inspection robots have a poor mobility function to pass any kind of pipe-bends such as curves and junctions so that those robots are only capable to move into the straight pipes. These two main reasons, "heavy and stiff cable" and "poor mobility function", make a limitation for robot movement that, in most case, the robot is driven only from one manhole to the next, and the robot is driven backward through the pipe to its entry point. Because the robot is tethered to the control unit in the car and disconnecting the power cord in the next manhole has a risk to expose the wires to water. Then the robot is retrieved, and the process is repeated again at the next manhole. This method for inspection of the sewer pipes makes the inspection process very slow (300 meters a day) and costly (2000 yen/20 dollars per meter) in Japan.[28] In order to realize inexpensive and effective inspection system, an autonomous pipe inspection method should be introduce to improve the

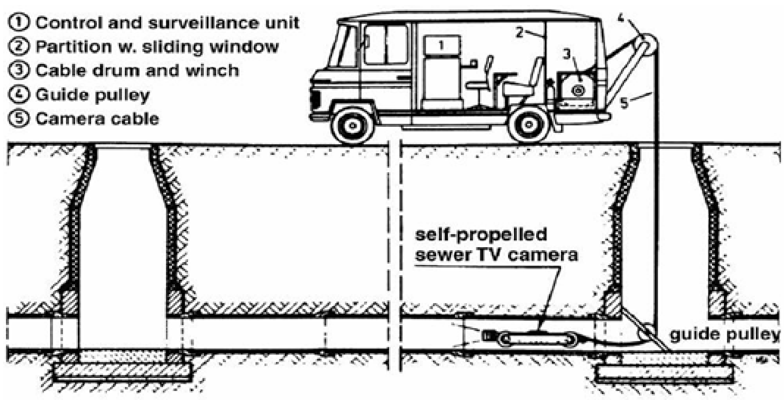


Figure 5.1: In current conventional method, the inspection of sewer pipes is undertaken using a cable-tethered robot with an on-board video camera system. An operator remotely controls the movement of the robot including a video system.

inspection efficiency by reducing the time and manpower of the inspection process.

5.1.2 Qualitative Degrees of Autonomy in Sewer Robots

To focus the study, also, for the sequel, we want to make more precise the different qualitative degree of autonomy in developed inspection sewer pipe robots that we will mention:

No autonomy: The robot is completely tel-operated, usually via a tether cable, by a human operator. The pipe condition is assessed by the human operator who watches the sensor data (usually video) as the robot drives through the pipe. Mostly all the commercial sewer inspection robots are not autonomous system.

Semi-autonomy: The tethered robot (in a few case UN-tethered) is partially controlled by automatic control programs and modules, or the assessment of the pipe condition is partially performed by sensor data interpretation programs. There is a number of researches and developments of the robots with the semi-autonomous function capability.

Full autonomy: The UN-tethered robot carries all required resources on-board. Navigation is performed completely by control programs running on on-board computing equipment. Status messages may be communicated to a human inspector over a radio link. Assessment of the pipe condition may be performed partially on-board, or offline after retrieval of the recorded sensory data. A few research have been done in development of a fully autonomous mobile robot for pipe inspection.**Full autonomy:** The UN-tethered robot carries all required resources on-board. Navigation is performed completely by control programs running on on-board computing equipment. Status messages may be communicated to a human inspector over a radio link. Assessment of the pipe condition may be performed partially on-board, or offline after retrieval of the recorded sensory data. A few research have been done in development of a fully autonomous mobile robot for pipe inspection.

In general, we observe that fully autonomous robots are not yet marketable system today. There are two main reasons for this:

- The degree of development of complete autonomous sewer robots presently does not warrant to use them safely and robustly in sewers. As mentioned in above, most of these robots have a complex moving mechanism and Multi-sensor equipment for navigation and motion control. These complexities in mechanism and data processing make not easy to realize reliable commercial products specially for small range of the pipes up to 300 millimeter in diameter.
- There seems to be some general skepticism about using fully autonomous systems without a possibility to interfere the robot control at any time, as would be the

case for a tether-less sewer robot out of the range of some radio link.

However, semi-autonomy does make sense, implementing in a tele-operated sewer robot separate modules (like special sensors with data interpretation software, or special motion control module) that operate autonomously within the overall control of a human operator. The purpose of such embedded autonomous modules would be to leverage the work load of the human operator in controlling the robot and interpreting sensory data, or to make certain measurements like in sewer inspection automatic, and therefore operational and reproducible. This is a serious issue in ensuring the quality of sewer maintenance, given that the pressure to provide service as cheep as possible imperils the quality of the inspection results.[28, 29]

5.1.3 Sewer Inspection Robots

Autonomous Sewer Robots Platform[2]

As we mentioned before, toady's state of the art in sewer maintenance involves tele-operated, tethered vehicles both for inspection and manipulation. To enhance the ease of use and the reflectivity efficiency of these platforms, there are in general two ways of helping to handle and control them: first, support the human operator in his or her control of the vehicle by making automatic part of the control; and second, make the platform or parts of it completely autonomous, thereby taking the operator completely out of the control loop or parts of it.[3]

KURT

The development of the experimental sewer robot test platform KURT (Kanal- Untersuchungs-Roboter-Testplattform) started at the former GMD now Fraunhofer institute AIS in 1995 [30]. KURT is a monolithic, non-holonomic six-wheeled autonomous un-tethered robot of approximate dimensions 30x45x30 cm. KURT version 1 has been successfully employed for navigating autonomously in a dry sewer test net at the premises of the Fraunhofer campus in Sankt Augustin. To achieve this, the robot is provided with a map of the test net, representing the topology of the 80 meters of sewer pipes and the nine manholes in between, with a start position (number of a manhole) and a goal manhole. The robot can determine the sequence of manholes - or pipe junction types, respectively - that it should pass on its path from start to goal. Since all pipe junctions inside the sewer test net are ground level connections, the robot is mechanically able to

[2]Using the term "platform" means to emphasize the fact that the respective systems do not include sensors for finding damages or assessing the pipe state, but just sensors to warrant their safe navigation and control. Such pipe-related sensors maybe be implemented on autonomous platforms.

[3]Most of the materials presented in this section have been selected from material provided by “Steinbeis Japan Inc., Kitakyushu foundation for the Advancement on Industry, Science and Technology”, March 2002.[28]

Figure 5.2: The commercial research robot platform KURT2. Figure shows a KURT2 system with a custom mounted 2D laser distance scanner.

perform turns at such junctions. With its pivoted ultrasound sensor, KURT1 is able to classify the type of a pipe junction, i.e. whether it is L-shaped, X-shaped, or T-shaped. A special patented method for navigation under uncertainty enables KURT1 to detect and correct errors due to false classification or due to errors while performing turns at pipe junctions [31]. This work has been complemented by a method for probabilistic mapping of objects - like landmarks - in the sewer [32]. Ever since its very first version, the KURT type robot platform has been further developed for indoor applications. The system is now being marketed by GMDs spin-off KTO as a customizable general purpose robot research platform. The current version KURT2 can be equipped with a variety of sensors. The standard configuration includes inclinometers and sensors for odometry, either infrared or ultrasound distance transducers for obstacle detection, and optional bumpers. Figure 5.2 shows a KURT2 system with a custom mounted 2D laser distance scanner. Alternatively, an industry standard PC/104 CPU can be provided.

MAKRO

MAKRO (Mehrsegmentiger Autonomer KanalROboter / multi-segmented autonomous sewer robot) is the prototype of a fully autonomous, un-tethered, self-steering articulated robot platform (Fig.5.3). It is designed for autonomous navigation in roughly cleaned sewer pipes within a diameter range of 300 to 600 millimeters at dry weather conditions. MAKROs case design, consisting of six segments connected by five motor-driven active joints, allows for simultaneously climbing a step and turning, e.g. at a junction consisting of a 600 millimeter pipe and a branching 300 millimeter pipe with equal top levels. MAKROs autonomy and its kinematic abilities extend its potential mission range enormously, compared to conventional inspection equipment that is limited by the cable and poor kinematics [33]. MAKRO carries all the needed resources on-board. Standard NiCd batteries provide the power for its 21 motors, the sensors, and the electronics, including an industry standard PC/104+ computer system and seven micro controllers [34], allowing for an autonomous uptime of about two hours. The goal of the MAKRO project was to prove that a robot is able to navigate completely autonomously inside sewers under the above mentioned conditions. In a way similar to that of KURT (see previous subsection), MAKRO takes a start and a goal manhole position and a topological sewer map, computes a path from start to goal, and drives autonomously along this path from the start to the goal position. Proprioceptive and external sensors provide all the data that MAKRO needs to navigate and to control its pose and locomotion. The robot is steered automatically by control programs running on its CPU and micro controllers. MAKRO incorporates a number of internal, proprioceptive sensors. A thermometer for measuring the CPU temperature, pulse counters for odometry, optical sensors for reading joint angle encoding, and more. Sensors for data acquisition from the environment are mainly located in both identically equipped head segments. Each of them contains a stereo camera pair, lighting equipment, an ultrasound transducer for obstacle detection, four fixed infrared distance transducers, and a custom IR scanner for household inlet detection. Low data rate sensor signals

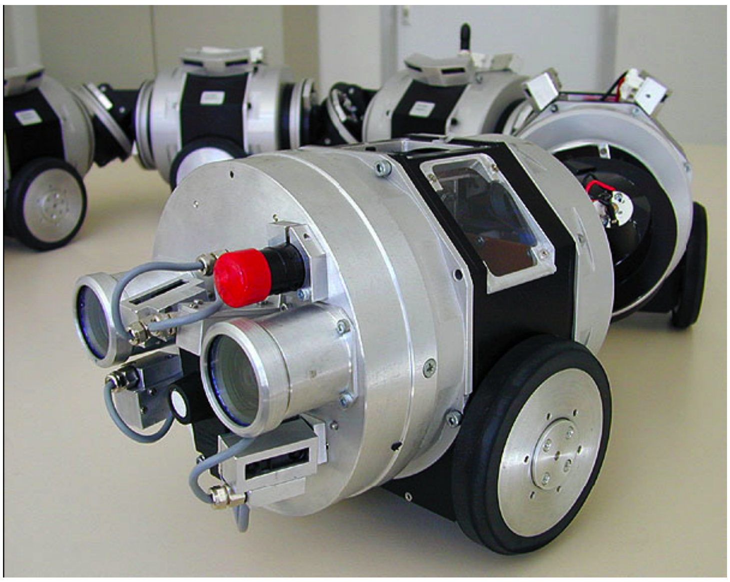


Figure 5.3: MAKRO is the prototype of a fully autonomous, un-tethered, self-steering articulated robot plaform. It is designed for autonomous navigation in roughly cleaned sewer pipes within a diameter range of 300 to 600 millimeters at dry weather conditions.

are gathered by the micro controllers and transferred via CAN bus to the CPU for further interpretation. Only the camera signals are directly transmitted to the PC/104+s frame grabber. The multi-sensor equipment is being used for navigation and motion control. Self localization, that is the automatic determination of the robots position inside the sewer, is based upon recognition of salient landmarks. Inside a sewer, only few structures are present that may serve as recognizable landmarks. These are house inlets, pipe junctions at manholes, and, less salient, pipe joints. The first two types of landmarks can be detected by interpreting the data of the custom IR scanner [35]. Ground-level pipe junctions may also be detected by the robots fixed infrared transducers. The camera equipment has been employed for various image data interpretation experiments, including 3D measurement of sewer pipe junctions, and visual recognition of household inlets [36]. Each MAKRO segment is propelled by a motor that drives a two-wheeled axis, and each joint connecting two segments contains three motors that allow for rotations around the three axes in space. The joint motors are strong enough to lift a part of MAKROs 50 kilograms heavy, 2 meters long body, which is necessary for climbing steps at some pipe junctions. In order to perform turning and climbing maneuvers, MAKRO has to simultaneously control most of its 21 degrees of freedom. This is a highly complex control task, and it is performed automatically by special control routines developed at Fraunhofer AIS. The routines rely on data from proprioceptive sensors like joint angle readers, and on external sensors like the infrared transducers, which can be employed to detect branching pipes at junctions and to estimate the distances of the head segment to the pipe walls during turning maneuvers. The alignment of the head segment with respect to the sewer pipe axis is automatically determined by a method that interprets images of a structured light pattern projected onto the pipe walls [37]. The robot MAKRO has been developed by a German group of two research institutes and two industrial partners. The MAKRO project was funded partly by the German Ministry for Research and Education (BMBF) between 1997 and 2000. Since 2001, the MAKRO project is being continued as internal projects at Fraunhofer AIS and FZI [38].

Semi-Autonomous sewer robots

KARO

KARO (KAnalROboter/ sewer robot) is an experimental semi-autonomous carrier for sewer inspection sensory equipment [39, 40, 41]. It was developed by a group of research institutes and some industrial partners in Germany. The project was partly funded by the German Ministry for Research and Education (BMBF). The monolithic KARO robot prototype (see Fig. 5.4) resembles much a standard non-autonomous sewer inspection robot, and it is tethered via a cable to a surveillance unit. Using inclinometers and an on-board control program, KARO is able to automatically correct for tilt in its pose and wheel slippage when driving inside a sewer pipe, thus freeing the human operator from this crucial control task [42]. The main innovation of KARO is its wide range of novel inspection and navigation sensors, namely, a microwave sensor and a 3D optical sensor, complementing the standard video camera and some ultrasound transducers [43]. The method for 3D measurement of hollow spaces using axial symmetric structured infrared light has been patented. It is applied for measuring pipe deformations, larger pipe cracks and obstacles inside the pipe, the latter being detected early by the US transducers. The microwave sensors are aimed at detecting leakages. KARO has been continued as an internal research project within Fraunhofer IITB at least until 2000. Most recent research deals with fuzzy methods for data fusion of inspection sensors. A commercial version of KARO is not yet available.

Pipe Rover / Pearl Rover

The development of the semi-autonomous Pipe Rover [44, 45] inspection robot for water filled pipes or ducts started as a research project in 1996. The specific application was driven by the needs of the City of Hong Kong, with its many sewers that are well accessible from Hong Kongs sea side. The project produced a spin-off company called Pearl Technologies Ltd. that markets the Pipe Rover. This inspection robot can operate in two locomotion modes. For flat-bottomed ducts, with little marine growth or other obstructions, tracks propel the robot to its destination. For round pipes, or where there significant marine growth or the possibility of obstructions, legs are used. The robot is electrically powered, although the legs are powered by an in-

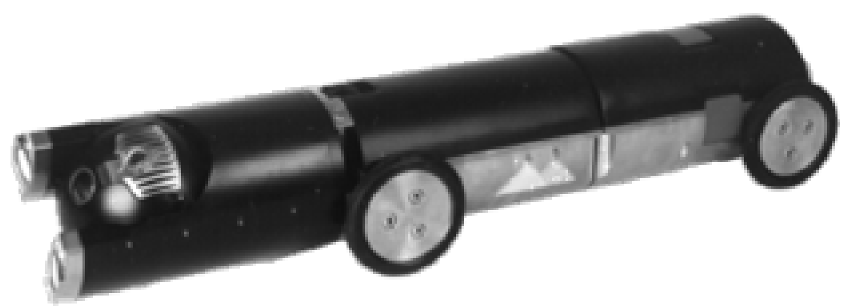


Figure 5.4: KARO is an experimental semi-autonomous carrier for sewer inspection sensory equipment. It was developed by a group of research institutes and some industrial partners in Germany.

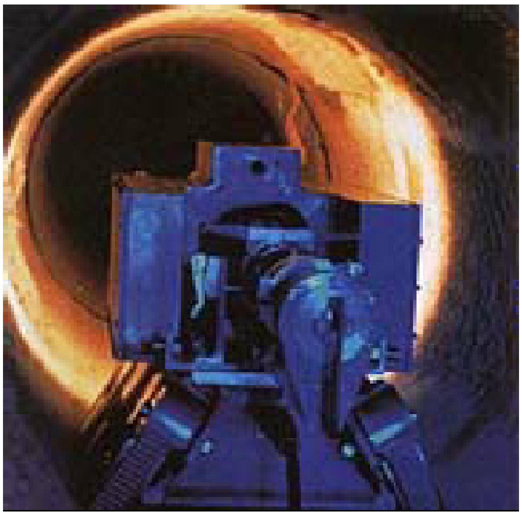


Figure 5.5: PIRAT is a semi-autonomous tethered robot for the quantitative and automatic assessment of sewer condition.

house designed hydraulic system that make use of the surrounding water. The robots sensor system includes an ultrasonic peripheral pipe contour scanner, one color zoom camera with pan and tilt, and one black and white rear facing camera for piloting in reverse. Communication can be achieved either via the fiber-optical tether, or, for the untethered version of the robot, via an ultrasonic link that will transmit low-speed, sampled color or black and white video to the control console with a sampling speed of less than one frame per second [46, 47]. With its on-board batteries, the untethered version of the Pipe Rover has a maximum mission duration of about four hours.

PIRAT

The PIRAT sewer inspection system has been developed between 1993 and 1996 within a joint project of the Manufacturing Systems and Automation Division of Australian CSIRO Manufacturing Science and Technology and Melbourne Water. PIRAT (Pipe Inspection Real- Time Assessment Technique) is a semi-autonomous tethered robot for the quantitative and automatic assessment of sewer condition [48, 49]. Just like a conventional sewer inspection device, PIRAT (Fig. 5.5) is deployed to a sewer, and tele-operated from a surveillance unit via a cable by a human operator. The maximum cable length of 250 meters gives PIRAT a fair operating range. The added value of the PIRAT system is its ability to perform automatic evaluation of its sensory data. PIRATs innovative instrument system contains a video camera and a laser scanner. For flooded sewers, the latter can be substituted by a sonar scanner, but at the price of less resolution and inspection speed. In 600 millimeter sewer pipes and at PIRATs usual inspection speed, the laser scanner produced a resolution of about 1.5 mm radially

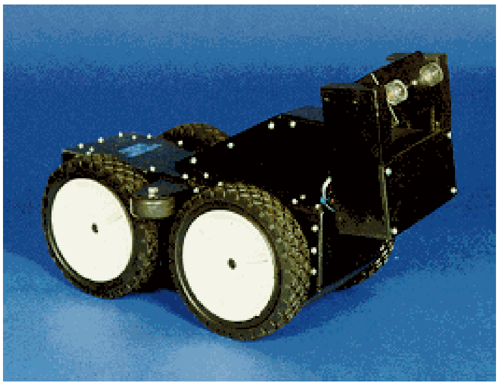


Figure 5.6: PIPER is a semi-autonomous tethered sewer inspection robot. Two user-programmable micro controllers provide for controlling locomotion and for automatically adjusting pan and tilt of the video camera head to the robots locomotion speed.

and 4mm axially and circumferentially. The sensory data are evaluated by means of PIRATs interpretation system, that is an expert system that runs on a Sun workstation in the mobile surveillance unit. From both types of scanner data, the interpretation system generated in a first step a three-dimensional model of the scanned sewer pipe section. In a second step, the interpretation system uses techniques from Artificial Intelligence to detect and classify damages on the basis of the three-dimensional model data. The result is a sewer condition assessment report that is readable for the human operator.

PIPER

Piper is a semi-autonomous tethered sewer inspection robot (Fig. 5.6), manufactured by Angelus Research Corporation. Two user-programmable micro controllers provide for controlling locomotion and for automatically adjusting pan and tilt of the video camera head to the robots locomotion speed. The video images can be either taped or captured on a computer. Its dimensions (9 inches width and 13.5 inches height) prohibit its application in smaller pipes. Pipers operating range is limited by the mandatory cable of about 45 meters.

PipeEye

The company Automatika, based in Pittsburgh, PA, is developing the prototype of a neutrally buoyant untethered pipe inspection robot called PipeEye (Fig. 5.7). The system shall be capable of providing video and acoustic imaging of underground sewer or water pipelines. This 12 inch robotic sphere is designed to operate floating in water filled pipes with diameters of at least 24 inches. A wide-angle color CCD video camera and spotlights are mounted in the part that stays above the water surface. Mounted

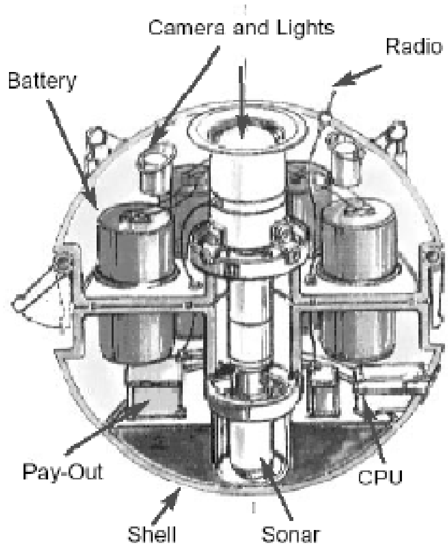


Figure 5.7: PipeEye is the prototype of a neutrally buoyant untethered pipe inspection robot, capable of providing video and acoustic imaging of underground sewer or water pipelines.

in the lower part, ultrasonic transducers shall yield imaging data from the underwater part of the conduit. The robot shall be steered by control programs running on an on-board PC/104 industry standard computer powered by on-board Li-ion batteries. Imaging data shall be either recorded to a flash disk or transmitted in compressed form via radio link through a manhole. The PipeEye system is derived from an oil/gas pipeline inspection module co-developed by Automatika and Shell Oil. Currently, the system does not yet have a product status.

5.2 Summary of design based on "Mecha-telligence methodology"

In this section the mecha-telligence methodology will be described for design and implementation of a autonomous mobile sewer robot. The first step in "Mecha-telligence methodology" as shown in Fig. 2.12 is to describe the tasks, desired behaviors, environmental niche, and environmental niche constraints.

Robot task

In general the sewer maintenance is classified to two categories:

- Inspection: It means assessment of the sewer pipe interior network and detecting the existing faults such as crack, water infiltration, root invasion, pipe break, and etc.

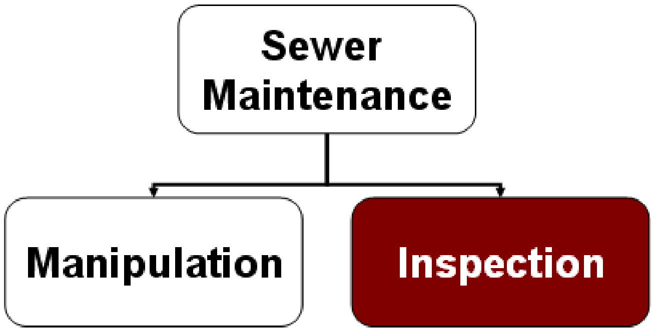


Figure 5.8: The definitions of robot task.

- Manipulation: It means repairing of the sewer pipe. It processes after the inspection the pipes.

In this industrial research study we concentrate to the inspection of the pipes with in diameter of 200, 250, and 300 [mm]. Then the robot task can be defined as “inspection” not “manipulation” (see Fig. 5.8).

Desired behavior

Based on state-of-the-art and autonomous sewer inspection scenario the desired behaviors can be described in three following items: (Fig. 5.9)

- Insert the robot from a manhole
- Robot moves in sewer network autonomously (without operator intermediary) as the **same water-flow direction**.

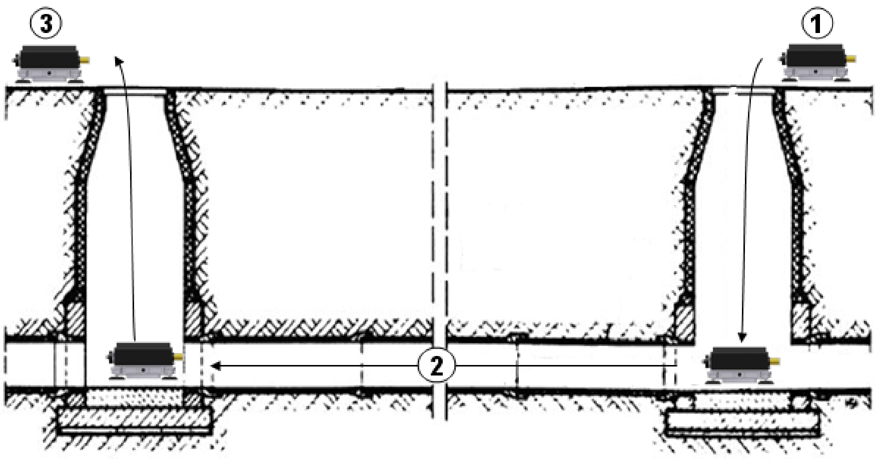


Figure 5.9: The definitions of robot task.

- After retrieval the robot, the number and position of the faults can be extracted from the robot sensory data.

Environmental niche and relative constraints

Alternatively, the environmental niche and the relative constraints can be defined and itemized as follows: (Fig. 5.10)
Environmental niche:

- Outdoor environment (Direct-physical meaning)
- Circle sewer pipe: main pipe (Direct-physical meaning)
- Manhole (Direct-physical meaning)
- Inlet (Direct-physical meaning)
- Pipe bend: Curve, Y- and T-Junction (Direct-physical meaning)

Environmental niche constraint:

- Diameter of main pipes are 20 or 25 or 30 [cm] (Direct-physical meaning)
- Diameter of manholes are 90 or 120 [cm] (Direct-physical meaning)
- There is a manhole over all pipe-bends (Direct-physical meaning)
- Maximum distance between to manhole is 50 [m] (Direct-physical meaning)

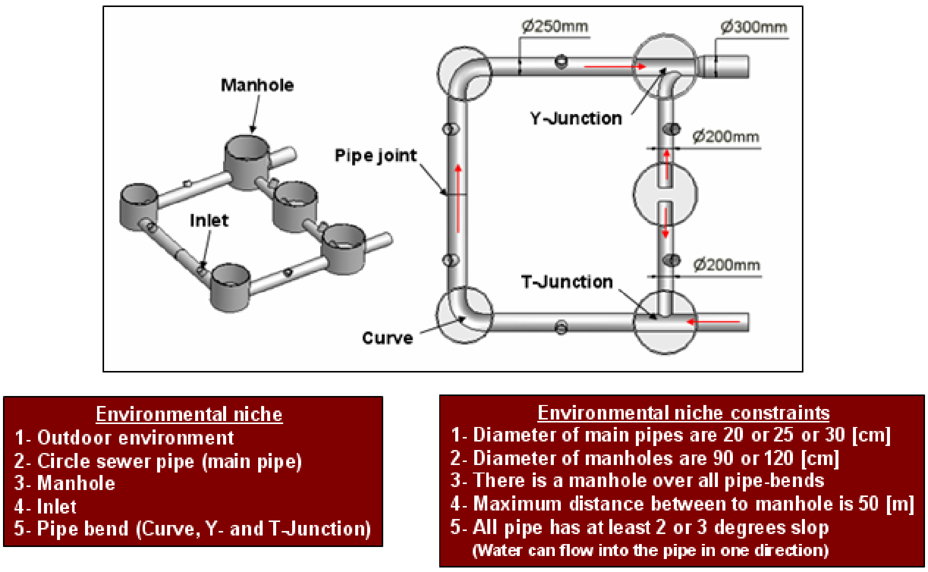


Figure 5.10: The definitions of environmental niche and relative constraint (Sewer robot).

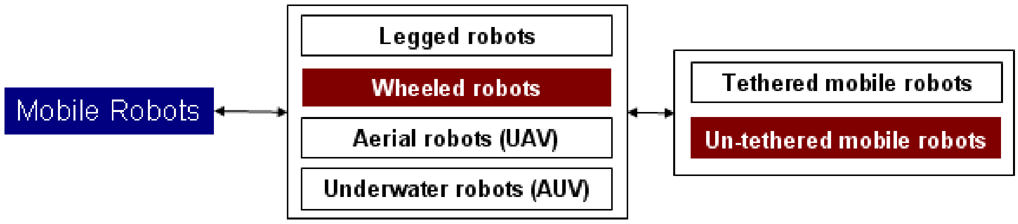


Figure 5.11: The selected type of sewer robot.

- All pipe has at least 2 or 3 degrees slop: Water can flow into the pipe in one direction (Direct-physical meaning)

Degree of autonomy and mobility

Degree of autonomy of the presented system can be summarized as follows:

- 1- The un-tethered robot carries all required resources on-board.
- 2- *Navigation* is performed completely by control programs running on *on-board* computing equipment.
- 3- Status messages may be communicated to a human inspector over a radio link.
- 4- *Assessment* of the pipe condition may be performed partially *on-board, or offline* after retrieval of the recorded sensory data.

Also, the robot should be designed as a wheel type-untethered robot (Fig. 5.11).

5.2.1 Simplification process of design functions

High-level specification layers (Main layer and Sub layer)

Regard to the description of four above terms, the high-level specification layers including main-layer and sub-layer can be illustrated as Fig. 5.12.

Low-level specification layers (Layer 1, layer 2, and mono-spec layer)

Figure 5.13 shows the definition of layer 1 extracted from sub-layer. The significant point in this generation is that because sewer inspection is done the same direction of water flow, robot does not need to perform going step-up. Consecutively, Figs. 5.14 and 5.15 show the generation of layer 1 and mono-spec layer, respectively. In these three figures the red color shows the terms which are on the process of simplification, white color illustrates the terms that are not important for our design purpose, and

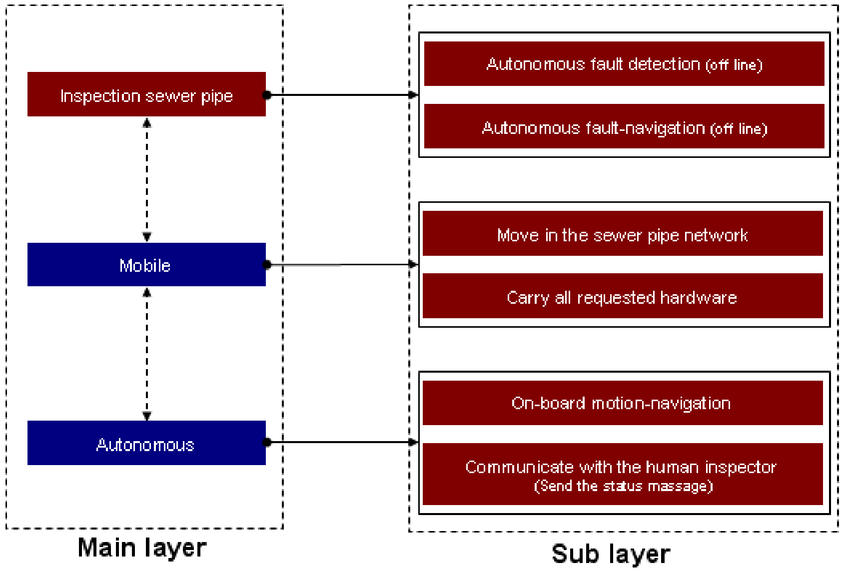


Figure 5.12: The high-level specification layers including main-layer and sub-layer (Sewer robot).

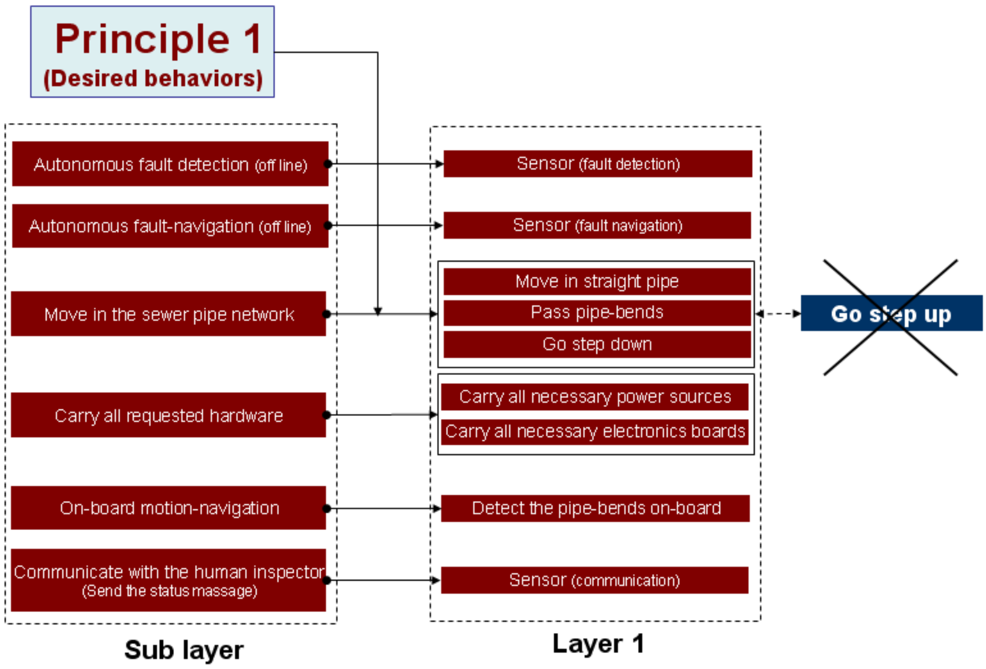


Figure 5.13: Layer 1 generated from the sub-layer (Sewer project).

yellow color indicates the terms which recognized as a simple basic function or selecting a sensor for a single task or behavior.

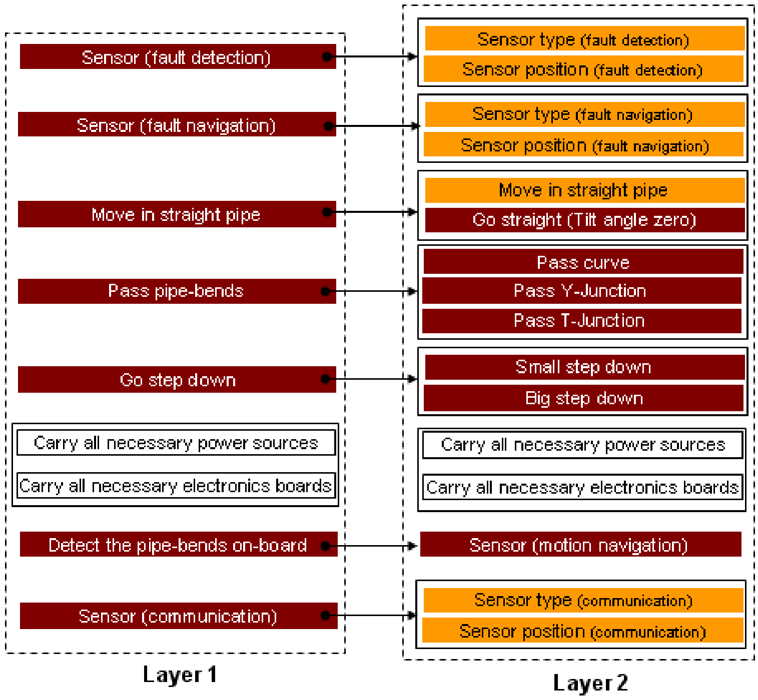


Figure 5.14: Layer 2 generated from the layer 1 (Sewer project).

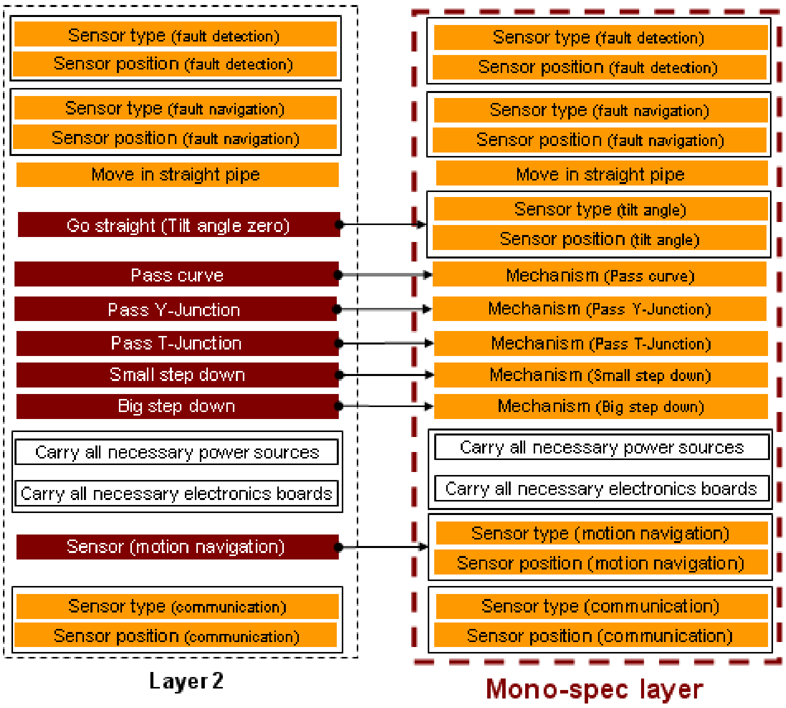


Figure 5.15: Mono-spec layer generated from the layer 2 (Sewer project).

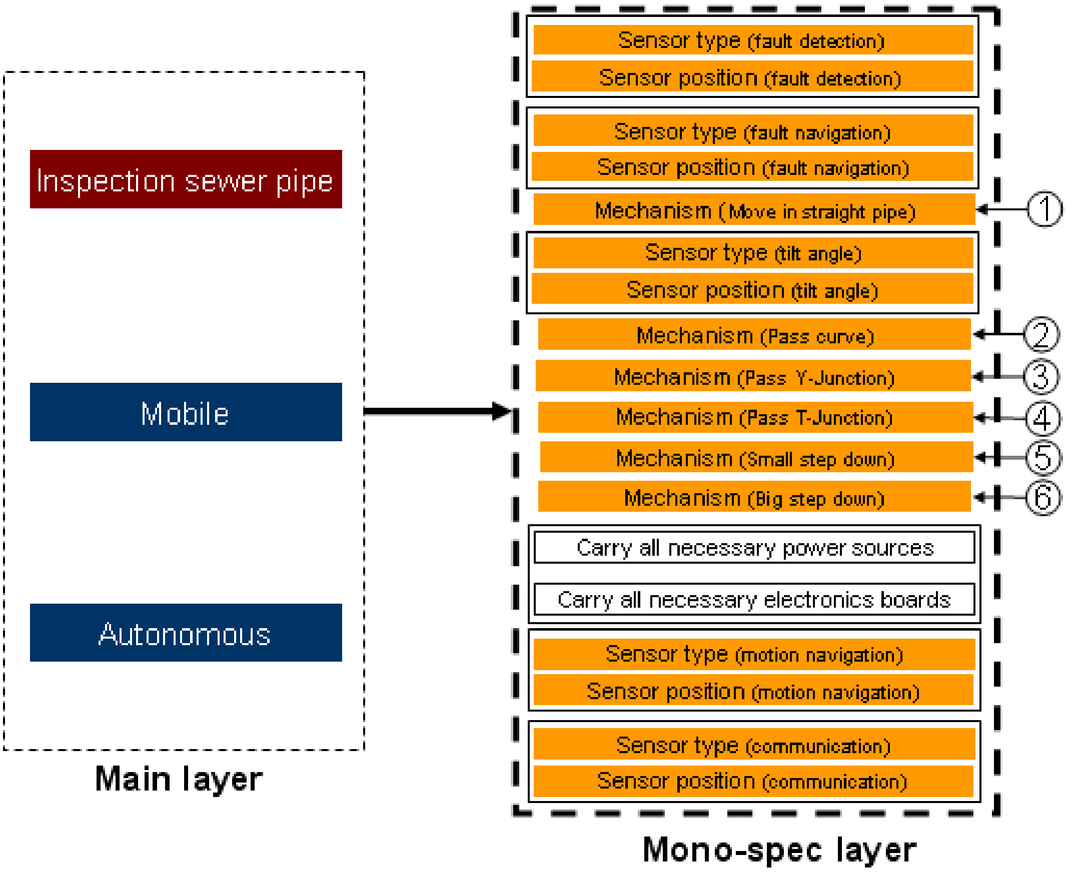


Figure 5.16: The function priority of design (Sewer project).

Functions priority of design

Figure5.16 shows the result of our simplification process from "main layer" to "mono-spec layer". Also, this figure illustrates the function design priority in point of view of mechanical parts design.

5.2.2 Design process: Applying the "Mecha-telligence principle"

This sub-section provides, only, an overview to our robot design and its architecture. Also it shows how the "mecha-telligence principles" have been applied in the process of the design. The whole detail designs and all definition and description of the related concepts are explained in the next sections. To deep understanding about our approach and detail of the robot design, reading the these sections is recommended.

Designing function 1 to 6

Figure 5.17 shows two possible model of water flowing inside of the pipe (*Applying* *principle 4: system-environment interaction*). As a common sense, the right side model

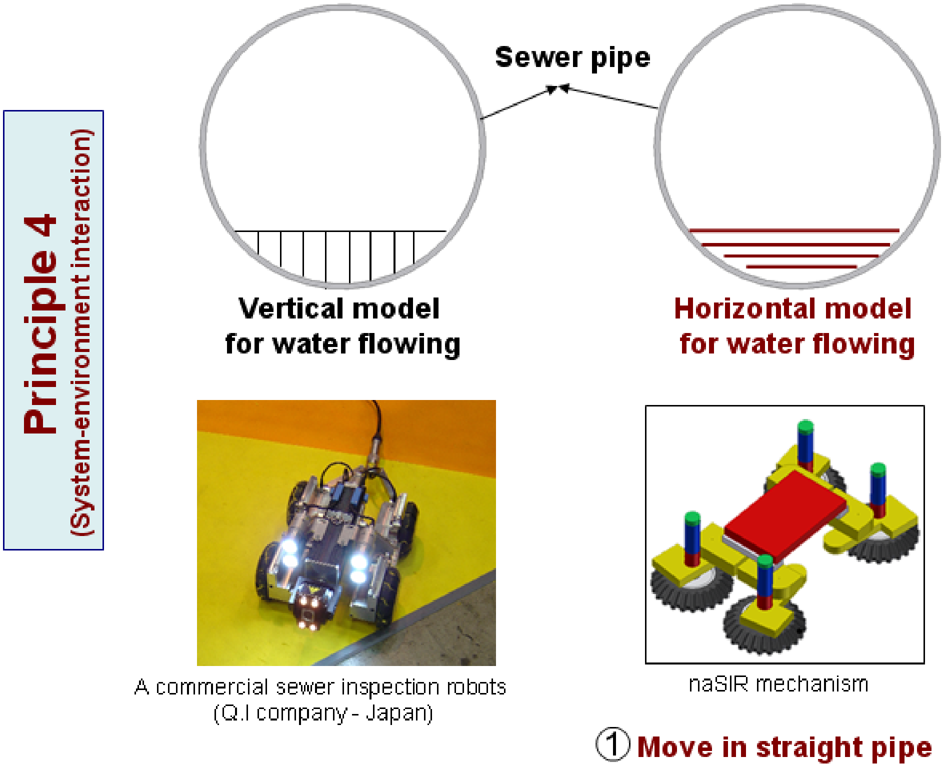


Figure 5.17: Two possible model of the water flowing inside of the pipe and comparing with a commercial vertical robot and naSIR mechanism presented in this thesis.

can be recognized as a intuitive model. By surveying on the existing commercial mechanisms and considering these two models we can realize that the robot wheels should be rotated 90 degree to get more national movement same as water flowing inside of the pipe. In this approach we can find out that the robot, not only, can move in straight pipe, but also can pass various kinds of pipe bends without any control or sensor reading. Consecutively, figure 5.18 shows the extension of the design for performing more smooth movement of "naSIR mechanism" during passing a curve, Y-junction and T-junction (*Applying principles 4 and* 6). This mechanism can pass a small step, depend on the robot size between 5 to 10 [cm], because of its suspension system. Passing a big step is realized with installing a passive elevator inside of the manhole. The robot can get on to the elevator and the elevator will be activated by the robot weight (*Applying principles 3, 4, and 6*).

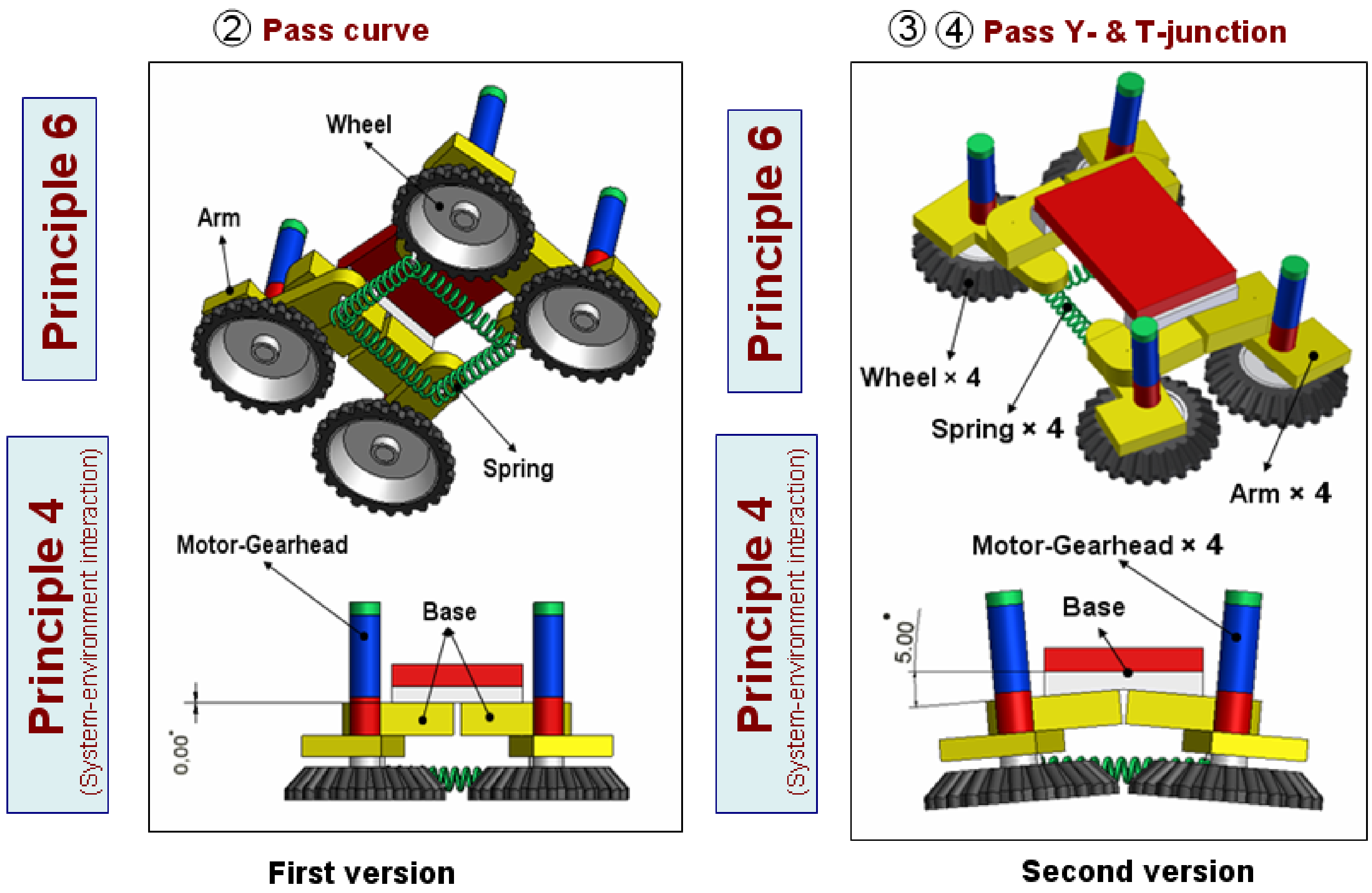


Figure 5.18: Design extension for performing more smooth movement of "naSIR mechanism" during passing a curve, Y-junction and T-junction.

Designing the other functions

Figures 5.19 and 5.20 show our approach for passive adjustable the robot tilt angle angle and the robot navigation. We applied the *principle 4* in form of material morphology

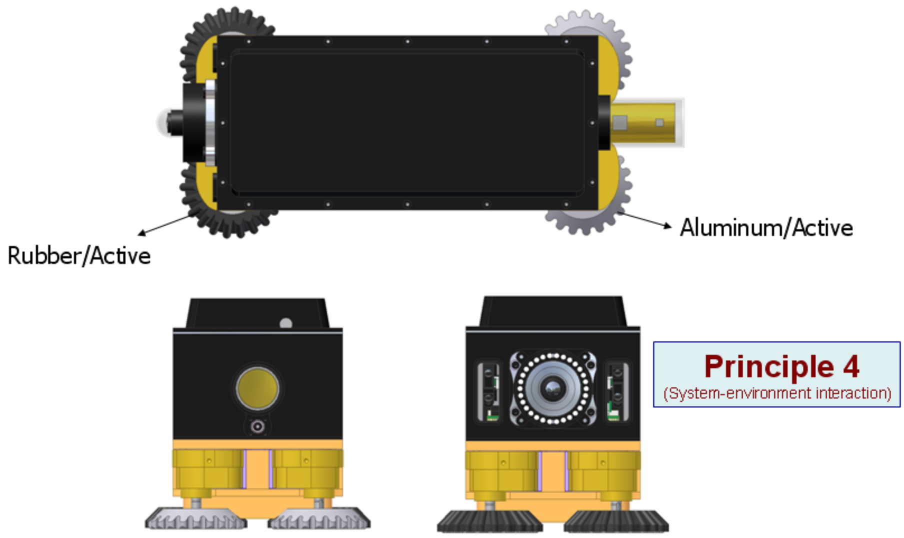


Figure 5.19: The robot can adjust its tilt angle passively by using the different material for the front and back wheels.

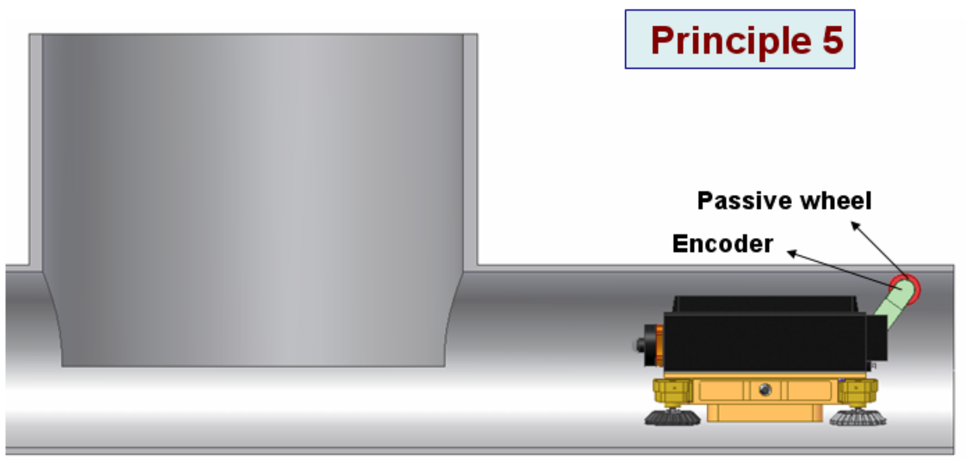


Figure 5.20: Shows the realization of a precise motion navigation for the robot by installed a passive encoder on the top of the robot.

to remove the tilt sensor from the robot hardware. we used the different material for the front and back wheels. In this approach the robot can adjust its tilt angle passively. Also we installed a passive encoder on the top of the robot by a simple arm jointed to the top-back of the robot. In this approach we could realize a precise motion navigation for the robot includes counting the numbers of manholes that the robot are passing.

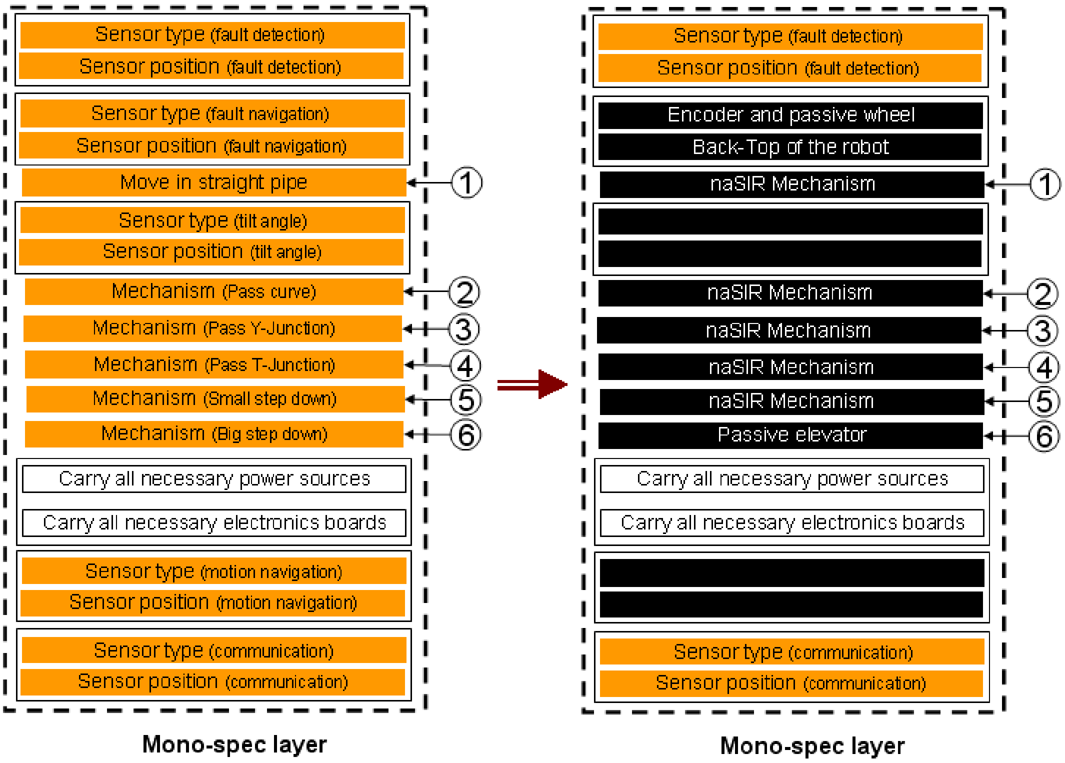


Figure 5.21: The results of design (Sewer robot). The black color shows our solutions for the listed problems in the mono-spec layer.

When the passive encoder does not send signal to the on-board main computer, it means robot is moving in the manhole.

For easy understanding of what we did and what we designed, the results are visualized in Fig. 5.21. The black color shows our solutions for the listed problems in the mono-spec layer.

5.3 A New Approach to the Autonomous Sewer Pipe Inspection

5.3.1 An Overview to the Sewer Pipe System in Japan

In Japan mostly 85% of the sewer pipes are under 600mm diameter and mainly more than 65% of this amount have a diameter within range of 200-300mm [28]. In this range of pipes, a sewer pipe net is constructed, mostly, by combination of pipes, pipe bends, manholes, pipe joints and inlets (Fig. 5.22). In general, any changing in the direction of a pipe or any intersection between two or more pipes called pipe-bend. Pipe-bends in a sewer, as a whole, can be classified in two main types depending on their constructions and shapes:

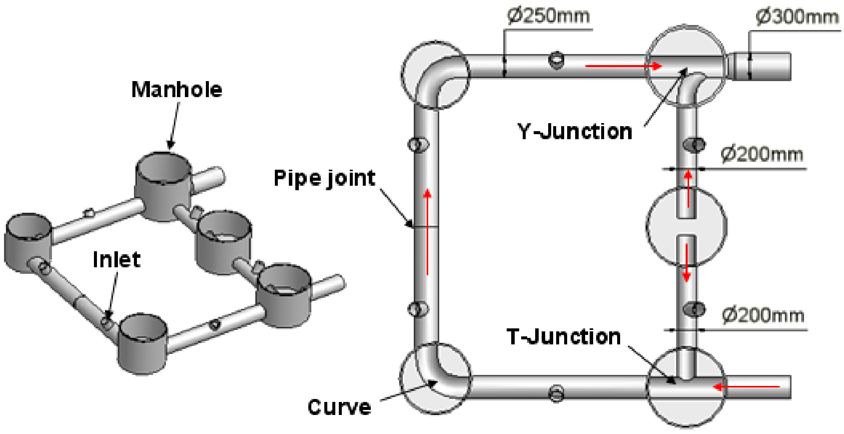


Figure 5.22: An example of a network of sewage pipes, in Japan, within a diameter range of 200-300 millimeters. In this range of pipes, a sewer pipe net is constructed, mostly, by combination of pipes, pipe bends (Junction sand curves), manholes, pipe joints and inlets. Red arrows show the direction of water flow into the pipe net.

- **Curve:** It defines as a pipe curvature and it has the maximum amount of pipe-bends in sewer pipe system in Japan.
- **Junction:** It is formed where three or more pipes intersect each other and makes different curves in intersection surface, such as Y-Junction, T-Junction, and X-Junction.

All pipe-bends are hand-made and constructed by concrete in spite that straight pipes are made by PVC or ceramic and factory-made. Therefore, in general, there is no rule or standard for curves and junctions in sewer pipe system in Japan, especially, in old sewer pipe construction. According to the sewer pipe construction lows in Japan, there is a manhole at the beginning of the pipe lines, between each 50 meters pipe and over all pipe bends. A pipe joint is formed in the connection surface of two straight pipes and an inlet is used for connecting a house pipe to a main pipe.

5.3.2 Basic Concepts of Design

In the current sewer pipe inspection technology, all commercial sewer inspection robots have a poor mobility function to pass any kind of pipe-bends such as curves and junctions so that those robots are only capable to move into the straight pipes. Same as MAKRO case, there is a number of efforts and researches to develop multi-joint (snake-like) robots with capability of passing curves and junctions [50, 51, 52]. Most of these robots have a complex mechanism and several sensors to detect the pipe bends and pass them. These complexities in mechanism and data processing makes not easy to realize reliable commercial products.

In this industrial research project we design the robot platform based on two following concepts:

- Passing the different kinds of pipe bends such as curves and junctions.
- Moving into the pipe network as same as water-flow direction.

we proposed the idea of "water-flow motion" to point out the fact that if the robot can move into the sewer network as same as the direction of water-flow, the robot does not required sensor to select its movement direction in case of "junctions".

5.4 Novel Sewer Pipe Platform: naSIR Platform

In this section, we will describe, in detail, our approach to design and realize a sewer pipe platform (naSIR platform) including a novel passive-active intelligent moving mechanism (naSIR Mechanism). This novel platform can move into the straight pipe and **pass**[4] the different kinds of pipe bends without need to any intelligence of the controller or sensor reading. With regard to developing a platform with capability of passing/navigating the pipe-bends, same as MAKRO case, there is a number of efforts and researches to develop multi-joint (snake-like) robots [50, 51, 52]. Most of these robots have a complex mechanism and several sensors to detect the pipe bends and pass them. These complexities in mechanism and data processing makes not easy to realize reliable commercial products. In this direction, there is no concrete evidence with regard to logical reasons or theorems that why the current commercial robots can not pass any kinds of pipe-bend, whereas the robot mobility function has become a critical subject for the speed up the sewer inspection process in point of perspective of related sewer companies.

5.4.1 Drawbacks of Current Commercial Sewer Inspection Robots

Most commercial inspection robots are built similar a car with four, six or more wheels (See Fig. 5.23). All wheels are fixed related to the robot and the robot has no steering function or special mechanism to turn in the pipe-bends. In such kind of robot, the robot can only perform a turning movement by changing speed in its right and left wheels. In this section, we will describe in detail why even a small car-like robot is not successfully able to pass a pipe-bend. The following results are the outcomes of considerable amount of work in simulation (simulation model shown in Fig. 5.24_A) and also driving a prototype robot in the real pipe network (see Fig. 5.24_B). In the

[4] Here, again, we point out that using the phrase of "passing" for a platform, while it is moving through a pipe-bend, instead of "Navigating", is that, the naSIR platform moves into sewer networks same as water-flow

Figure 5.23: Three samples of current commercial sewer inspection robots (Q.I company - Japan).

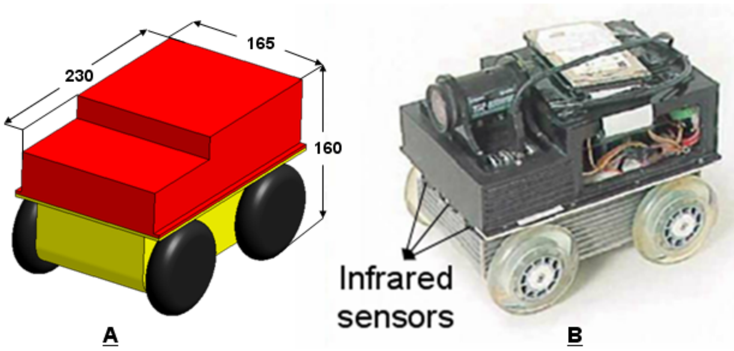


Figure 5.24: Figure (A) shows the simulation model and figure (B) illustrates a prototype of small car-like robot with four wheels and no steering function (L 230 W 165 H 160 [mm]). This robot has six infrared sensors for detecting the pipe-bends and four motor-encoder to control the wheels speed.

first experiment, there are no sensors used on the robot for detecting the pipe-bends and controlling the wheels speed. In the next experiment, we evaluated the performance of the car-like prototype robot using six infrared sensors, mounted around the robot, to detect the pipe-bends in order to control the wheels speed and move through the different curve angles.

No sensor used for the robot motion

Figure 5.25 shows three different starting point for the robot during passing a curve (case A), Y-Junction (case B) and T-Junction (case C). Also this figure illustrates the desired directions of the robot movement (black thick arrows) while passing the three different kind of pipe bends. The black thick line, shown in Fig. 5.25, can be presented as an optimal path-line for the robot motion during driving through the pipe network. The robot will be, successfully, pass the pipe-bends, if it can roughly keep moving on this line.

direction (the sewer net structure are constructed, so that, water has only one direction to flow in any kinds of pipe-bends of sewage networks).

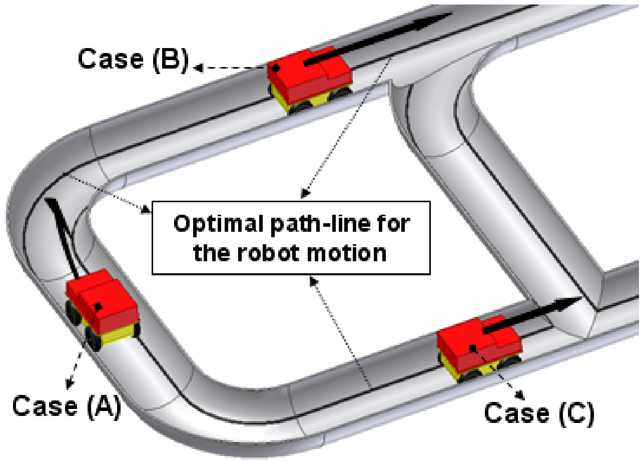


Figure 5.25: It shows three different starting point for the small car-like robot during passing a curve (case A), Y-Junction (case B) and T-Junction (case C). The desired directions of the robot movement marked by the black thick arrows. The black thick line can be presented as an optimal path-line for the robot motion.

While the robot is driving through a curve, it will tilt over into the pipe because the contact position between the robot wheels and the pipe-wall changes relative to the robot (Fig. 5.26). For more detailed understanding, let's consider the front wheels contact position. In the straight part of the pipe, as shown in robot position #1 in Fig. 5.27, all four robot wheels have a contact area on the optimal path-line (black thick line). In the beginning of the curve (see robot position #2 in Fig. 5.27) the contact area of the left and right front wheels change from the optimal path-line, respectively, to the side and bottom of the pipe as marked by white circles in the Fig. 5.27. On the other hand, because of the pipe shape and the rigidity of the robot, a high level of friction exists between the robot wheels and the pipe walls. In this condition, if the

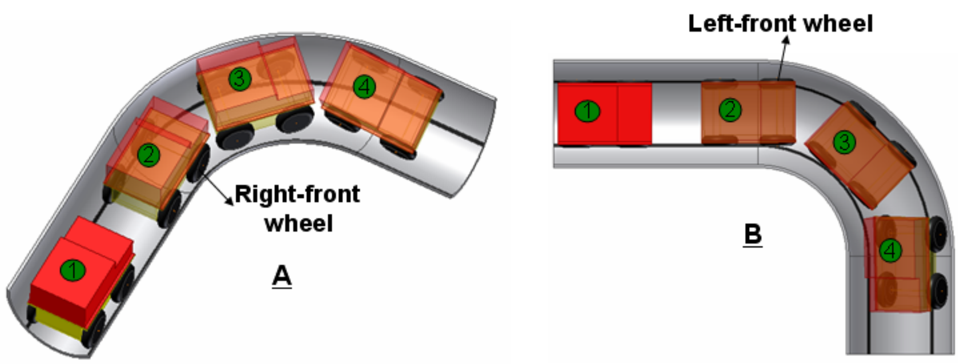


Figure 5.26: Robot motion, shown at four positions, while driving through a curve (A: 3D view, B: Top view). The robot will tilt over into the pipe, because the contact position between the robot wheels and the pipe-wall changes relative to the robot.

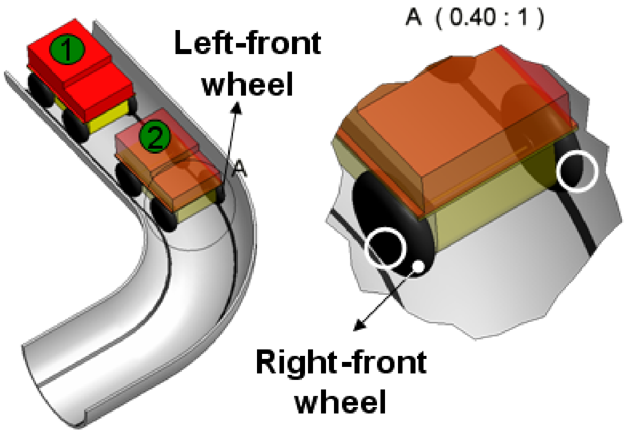


Figure 5.27: In the straight part of the pipe, the robot position #1, all four robot wheels have a contact area on the optimal path-line (black thick line). In the beginning of the curve (robot position #2) the contact area of the left and right front wheels change from the optimal path-line, respectively, to the side and bottom of the pipe as marked by white circles.

robot continues to move, the left wheels start to tilt upward and the right wheels tilt downward (see Fig. 5.26) till the robot tilts over into the pipe. For the same reasons as noted above:

- The constant change of the contact position between the robot wheels and the pipe-wall relative to the robot
- The high level of friction that exists between the pipe-wall and the robot wheels

the small car-like robot has not enough mobility function to pass the junctions. The results of simulation and real experiments of the robot motion in a Y-Junction and

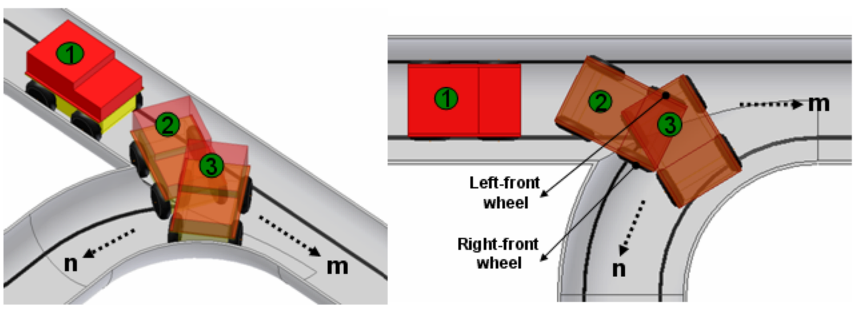


Figure 5.28: Robot motion, shown at three positions, while it is driving through a Y-Junction (A: 3D view, B: Top view). Because of specific surfaces formed in the intersection junction, the robot starts to turn toward the direction (n), (robot #2), and in the robot position #3 it is unable to find the proper direction to move forward beyond the junction.

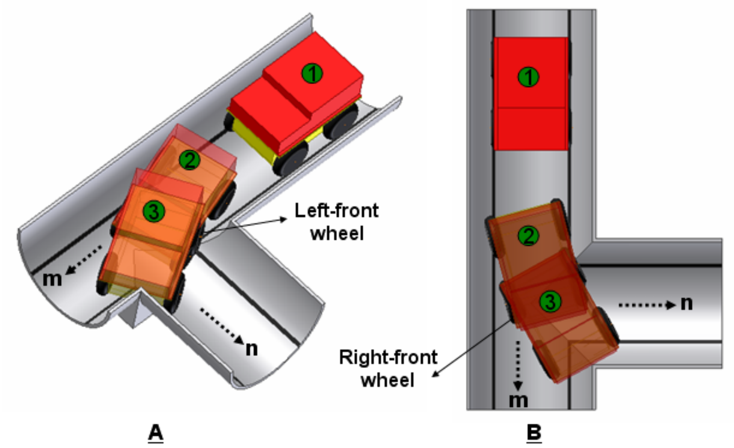


Figure 5.29: Robot motion, shown at three positions, while it is driving through a T-Junction (A: 3D view, B: Top view). Because of specific surfaces formed in the intersection junction, the robot starts to turn toward the direction (n), (robot #2), and in the robot position #3 it is unable to find the proper direction to move forward beyond the junction.

T-junction are shown in Fig. 5.28 and 5.29, respectively. In both cases, because of specific surfaces formed in the intersection junction, the robot starts to turn toward the direction (n) (shown in robot position #2 in Figs. 5.28 and 5.29). At the intersection junction, each front wheel has the tendency to move toward a different direction (see the robot position #3 in Figs. 5.28 and 5.29). Therefore the robot is unable to find the proper direction to move forward beyond the junction or in another expression, pass the junction.

Six infrared sensors-four encoders used for the robot motion

In the second experiment, there are six infrared transducer sensors, which are mounted at the robot chassis to cover most of its front and back and almost side area of the robot (Fig. 5.24_B). They measure distances to objects up to 15 cm at a resolution of 2 mm. Then, we used four encoders, which are installed in the motor-gearhead-encoders combination, measuring the robot wheel speed, independently. After a number of experiments we realized that the installed sensors could use for detecting and controlling the robot during driving it through the curve with specific angle but are unable to distinguish the different degrees of the pipe curvature. Therefore distinguishing different degrees of curvature in a pipe network would require specific sensors with separate programing and algorithm which is not practically applicable to realize reliable commercial product.

5.4.2 Novel Moving Mechanism (naSIR Mechanism)

In this section we describe a special patented moving mechanism called "naSIR Mechanism" [53]. naSIR is a passive-active intelligent, compact and novel moving mechanism that can move into the straight pipes and passes different kinds of pipe bends without need to any intelligence of the controller or sensor reading. This passive-active mechanism as a robot platform itself can move into the pipe and passes wide variety of the pipe bends even without controller for the wheels actuator. In addition, this moving mechanism has capability to pass the different size of pipes in diameter even from a bigger diameter pipe to smaller diameter and also can pass a small obstacle and go down a small step.

The design is based on the concept "passive adaptation of robot wheels to the bends in the pipe". As mentioned in previous section, because of the constant change of the contact position between the robot wheels and the pipe-wall relative to the robot and the high level of friction that exists between the pipe-wall and the robot wheels, current robots can not pass the pipe-curve without an exact speed control on their wheels. This problem has been solved in new design by a proper wheels orientation and passive damping of springs. The wheels orientation in new design was changed 90 degree compared with a car-like robot and each wheel has enough flexibility in horizontal level. Therefore naSIR mechanism has four wheels parallel with horizontal level which are connected to the four arms and each arm is jointed to the base plate, independently, and they connected to each other by using four springs (see Fig. 5.30). In naSIR mechanism, the contact positions between the wheels and pipe-wall relative to the robot are steadily the same, therefore it can move through the different degrees of the pipe curvature smoothly without any control and sensor reading (eg. a 90 degree curve, shown in Fig. 5.31). Moreover, while the robot moves through the curve, there

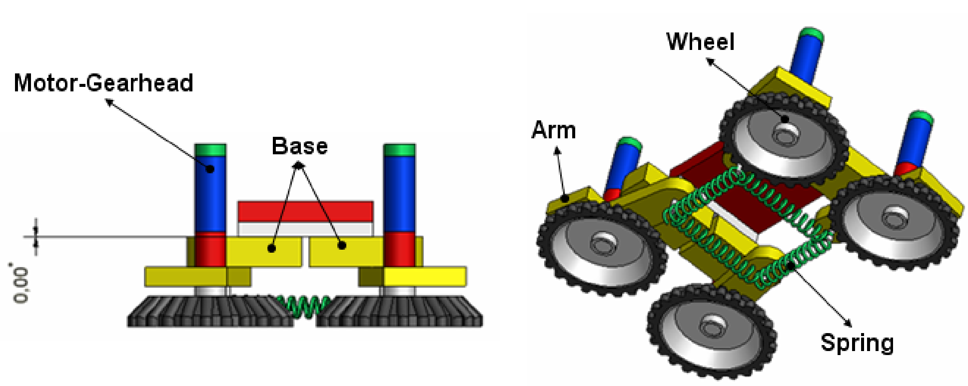


Figure 5.30: naSIR mechanism has four wheels parallel with horizontal level which are connected to the four arms and each arm is jointed to the base plate, independently, and they connected to each other by using four springs.

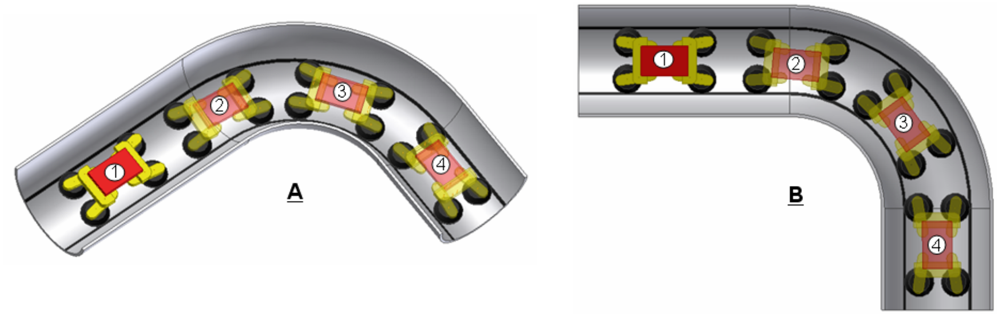


Figure 5.31: naSIR mechanism motion during passing a 90 degree curve (A: 3D view, B: Top view). Robot can adapt itself into the pipe interior to have a continuous movement on the optimum path-line.

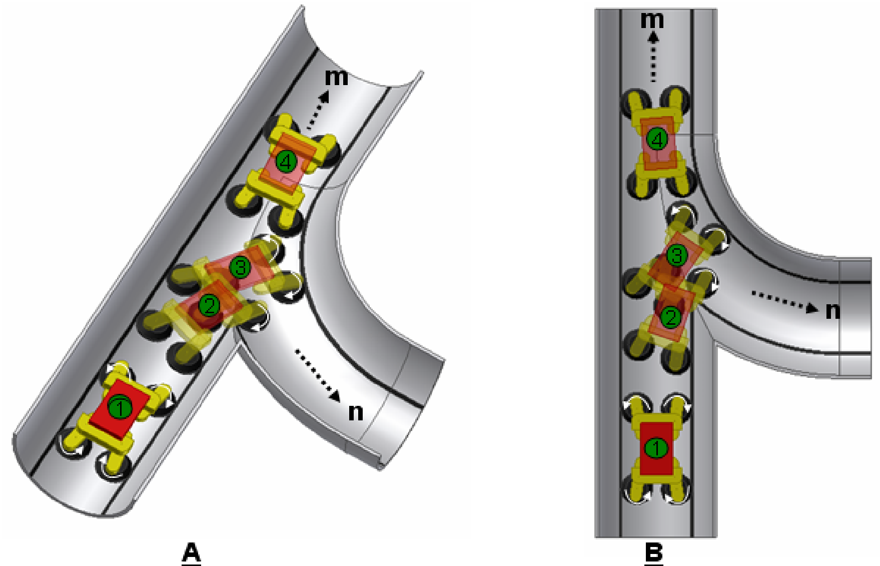


Figure 5.32: naSIR mechanism motion during passing a Y-Junction (A: 3D view, B: Top view). The white arrows indicate the direction of wheels rotation.

is a contact point on each of the four wheel circumference which at each moment in time has exact similar condition relative to the robot so that it can be encircled by the pair of optimal path-line, as shown in Fig. 5.31. Figures 5.32 and 5.33 illustrate the robot in Y-junction and T-junction, respectively, and the white arrows indicate the direction of wheels rotation. In both cases, because of specific surfaces formed in the junction intersection, first the robot starts to turn toward the n direction (robot position #2), immediately upon the contact of the right front-wheel with the optimal path-line (robot position #3) the robot corrects its path and moves forward in the m direction. Fig. 5.34 indicates the naSIR mechanism movement when it is moving from a bigger diameter to smaller diameter pipe. The design of naSIR mechanism was

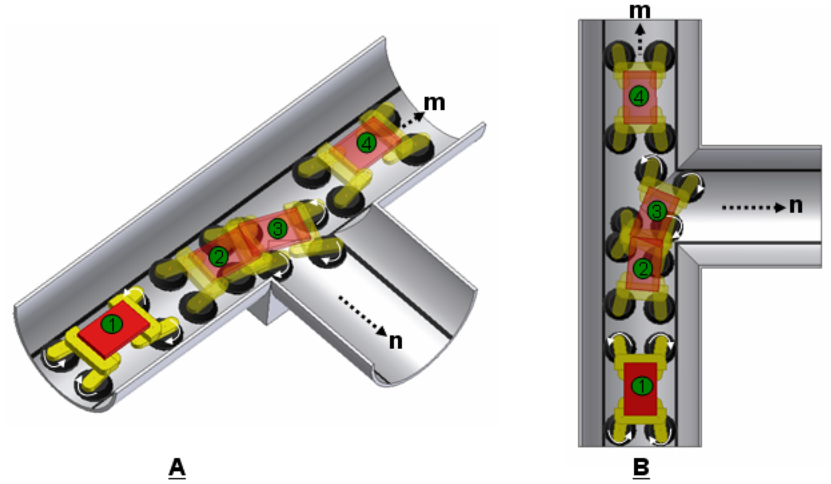


Figure 5.33: naSIR mechanism motion during passing a T-Junction (A: 3D view, B: Top view). The white arrows indicate the direction of wheels rotation.

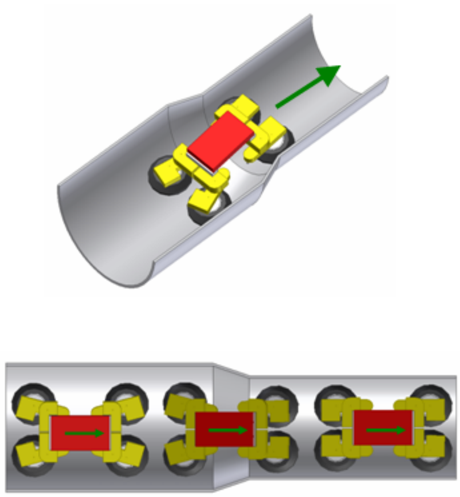


Figure 5.34: Motion of naSIR mechanism when it is moving from a big diameter to small diameter pipe.

developed by changing the wheels orientation from 0 degree to 5 degree with respect to the horizontal level (see Fig. 5.35). In this approach, the robot has a smoother motion in T-junction and also it is capable to move on flat surfaces.

5.4.3 naSIR Platform

Calculation of proper dimensions of the naSIR mechanism for making a prototype needs a precise study of dynamic and behavior of robot into the pipe. Because of the complexity of friction condition and the contact area between the platform wheels and pipe-wall, considering and driving of the platform dynamic equations is difficult and

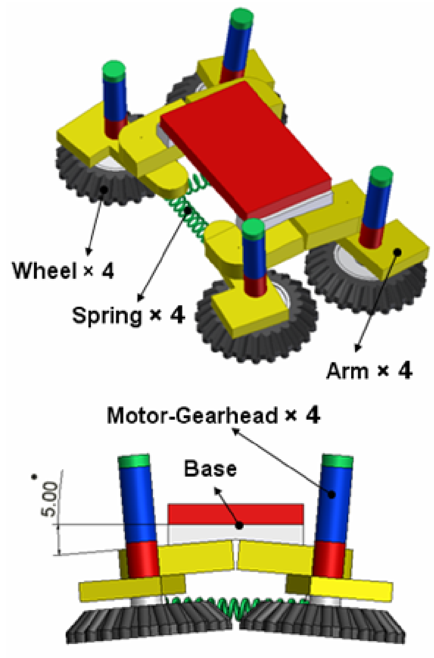


Figure 5.35: Second version of naSIR mechanism. The robot wheels have a 5 degree angle with respect to the horizontal level.

time-consuming. Using a powerful simulation such as Visual Nastaran 4, included of a precise modeling of friction, can make an easier study of the robot motion and very close to the actual condition which happen for mechanism in the real pipe. Based on simulation results, for the pipe in range of 250-300 mm in diameter, a prototype with following specification was made for employing naSIR mechanism as a platform in real sewer pipe network, Fig. 5.36:

- Length of the prototype is changeable from 20 till 50Cm.

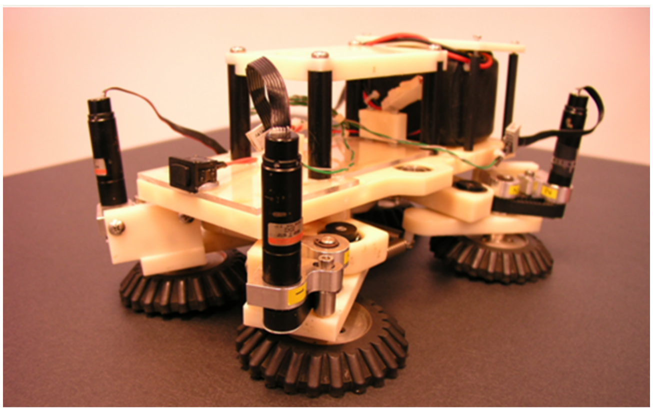


Figure 5.36: Prototype of naSIR mechanism, includes four motor-gearheads, four wheels and a battery pack, is able to pass wide variety of the pipe bends in a sewer pipe network.

- The wheels orientation is changeable in five different angles, -5, 0, 5, 10, 15 degree.
- Width of the prototype is changeable from 10 till 20 Cm.
- The spring stiffness coefficient is adjustable.
- Prototype has enough free space, for the extra weight, to get the different weight.

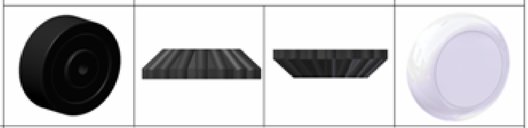
After several experiments of naSIR mechanism with different size, weight and spring stiffness coefficient into the real pipe net, naSIR mechanism with the dimension of L400 W180 H60 [mm] and a spring coefficient 0f 0.5-1 [N/mm] had a smooth and robust movement while passing the curves and junctions of a sewer network arranged by pipes which have with diameter within range of 250-300 [mm]. The practical results of naSIR mechanism movement with the different wheels angle with respect to the horizontal level and the different wheels in shape and material, are illustrated in Tables 5.1 and 5.2, respectively. In addition, naSIR mechanism, because of its special morphology, has an intelligence in selecting the correct direction of its movement same as water-flow direction with no control or sensor reading. After all we developed the naSIR mechanism as a platform called "naSIR Platform" (Fig. 5.37). naSIR platform consists of naSIR mechanism, a lithium polymer battery pack fitted under the platform, and a power switch can demonstrate a robust movement into the straight pipe and smooth and rapid motion while passes different kinds of pipe bends. In this approach naSIR platform does not request any kinds of sensor for its motion inside of the pipe, even encoders for motors of wheels, and can move same as water-flow direction into the sewer networks including the wide variate of pipe-bends . As an example, Fig. 5.38 shows a sample of sewer network including a T-junction, a Y-junction, and six 90 degrees curves. Red arrows, in this figure, show the direction of water-flow. The prototype of naSIR mechanism and naSIR platform, started from point (A) or (B), are employed to

Table 5.1: The practical result of naSIR mechanism movement with the different wheels angle with respect to the horizontal level into the pipe network.

	Straight pipe	curve	Y-Junction	T-Junction	Step down
-5°	white	black	black	black	black
0°	white	white	white	pink	pink
5°	white	pink	white	white	white
10°	white	red	red	red	white
15°	white	black	red	red	white

Smooth movement (white) → (pink) → (red) → (black) Hard movement with vibration

Table 5.2: The practical result of naSIR mechanism motion with the different wheels in shape and material through the pipe network.

	Hard plastic	Natural rubber		Ulithian
				
Straight pipe	Smooth but the wheels have slipping	Smooth movement	Smooth but a little bit vibration	Vibration
curve	Smooth movement	Smooth movement	Smooth movement	Vibration
Y-Junction	Not smooth movement	Smooth movement	Smooth but a little bit vibration	Vibration
T-Junction	Not smooth movement	Smooth movement	Smooth movement	Not smooth movement
Step down	Hard movement	Smooth but a little bit vibration	Smooth movement	----(No test)----
Obstacle	Very hard movement	Smooth movement	Smooth but a little bit vibration	Not smooth movement and also vibration

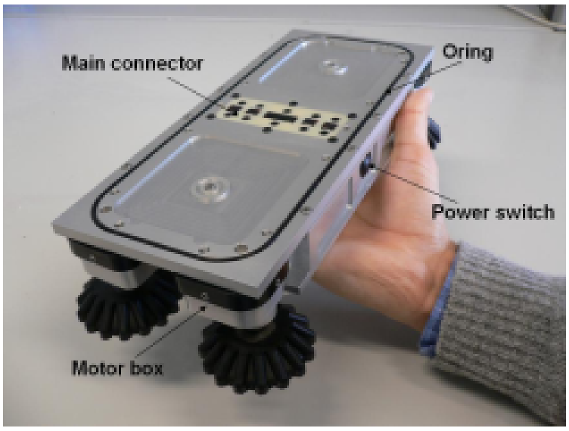


Figure 5.37: naSIR platform consists of naSIR mechanism, a lithium polymer battery pack fitted under the platform (is not show in the figure) and a power switch.

move same as the red arrows direction into this network without any control or sensor reading up to 2 hours without any stocking in the pipe-bends.

5.5 Autonomous Sewer Inspection Robot: KANTARO

KANTARO is designed as a fully autonomous, un-tethered robot, which fits to the pipes within a diameter range of 200-300 millimeters (see Fig. 5.39). KANTARO's autonomy and its kinematic abilities extend its potential mission range enormously, comparing to conventional inspection equipment that is limited by the cable and poor kinematics. KANTARO carries all the necessary resources on-board. Standard lithium polymer batteries provide the power for its 4 motors, the sensors, the light and electronics, including a developed computer system and an optical underground wireless

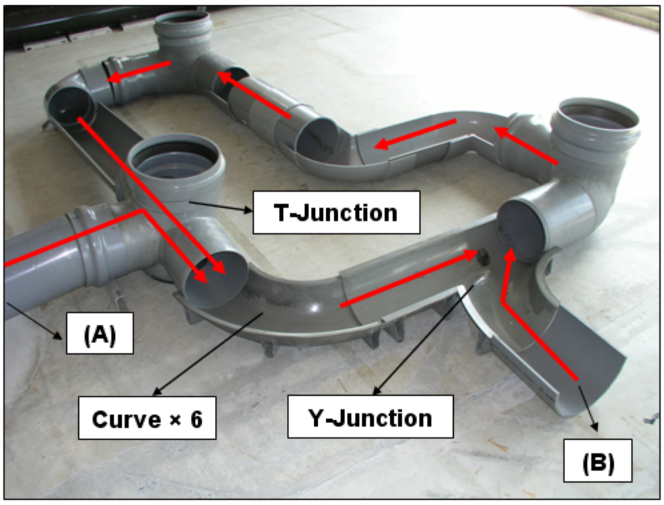


Figure 5.38: A sample of sewer network including a T-junction, a Y-junction, and six 90 degrees curves. Red arrows shows the direction of water-flow.

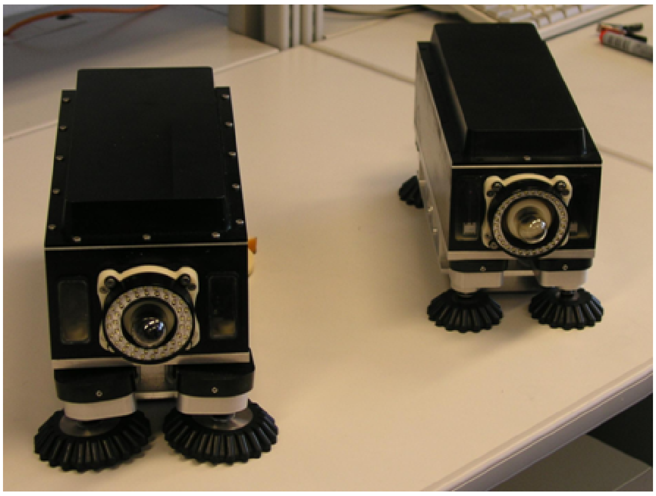


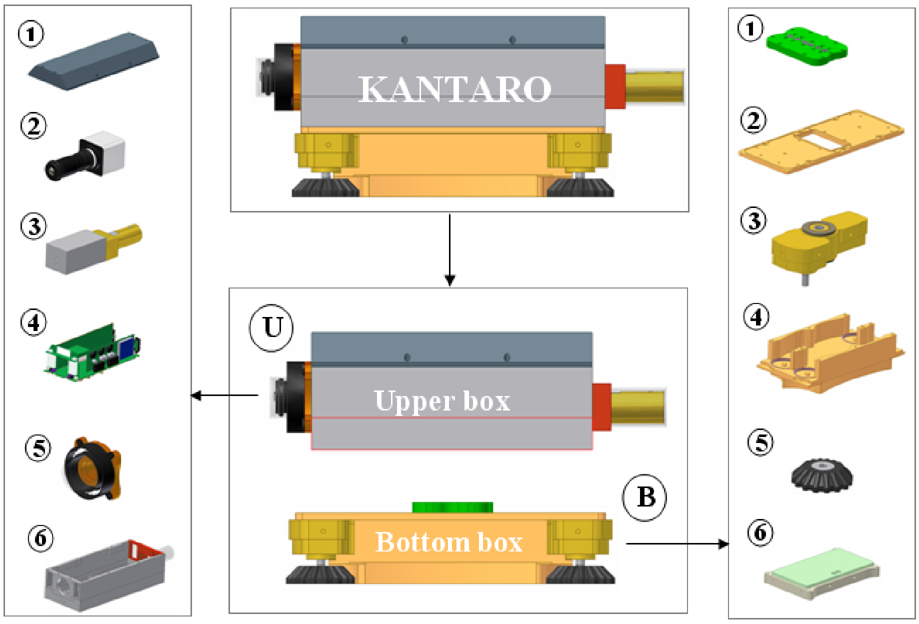
Figure 5.39: Developed KANTAROs fit to the 250 [mm] (left robot) and 200 [mm] (right robot) diameter of sewer pipe.

communication module, allowing for an autonomous up time of about one hour.

5.5.1 KANTARO Architecture

To realize a reliable, robust robot and an easy maintenance system, KANTARO is designed to have a complete modular architecture in its mechanic, hardware and software. KANTARO, as shown in (Fig. 5.40), consists of two main modules: Bottom and Upper box modules.

naSIR platform is employed as a bottom box of KANTARO. Electronic boards, the sensors and light are installed in upper box which be connected via the main



	Full name		Full name
U	Upper box	B	Bottom box
U-1	Upper box cap	B-1	Main connector
U-2	Camera	B-2	Bottom box cap
U-2	Laser scanner	B-3	Motor box
U-2	Hardware	B-4	Bottom box base
U-2	Light	B-5	Wheel
U-2	Upper box base	B-6	Battery pack

Figure 5.40: KANTARO has a modular architecture consist of two main modules: Bottom box and Upper box. Modularity of bottom and upper boxes showed in right and left of the figure, respectively.

connector to the bottom box . In addition, KANTARO has IP67 waterproof standard that it achieved by waterproof design of KANTARO's modules including the upper and bottom box, motor boxes and battery pack.

5.5.2 KANTARO Hardware

We designed all necessary electronic boards used for control, saving sensory data and wireless communication as a module,called E.B. module, fit to the upper box of KANTARO (Fig. 5.41). E.B. module contains a mother board, power and motor controller and CPU boards, hard disk and an optical underground wireless communication board. All boards are designed as separated modules to communicate to each other via their own connectors through the mother board. In the newest version of E.B. module, power board and hard disk are combined with mother board to be a more compact and wiring less module. Wiring less was one of our target in this project to realize a compact, reliable and robust hardware for KANATRO. To achieve the wiring less

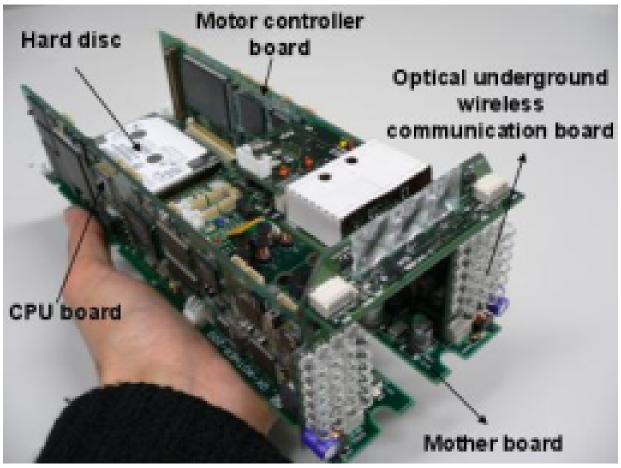


Figure 5.41: The newest version of KANTARO electronic boards module (E.B. module).

Table 5.3: KANTARO electronics boards specification

CPU board		Motor controller board	
CPU	SH7750R(SH-4)	CPU	SH7055R(SH-2E)
FPGA	EPF10K100AGC484	FPGA	EPF10K100AGC484
Memory	SDRAM 512k×2	Memory	SDRAM 512k
I/F	RS232c, LAN	I/F	RS232c, CAN
Image compression	ADV202	I/O	PWM×5,PIO (8×2)
video input	NTSC		
Size	215(L)*55(H)mm	Size	215(L)*55(H)mm
Mother board		**Optical communication board**	
CPLD	EPM7064STC44-5	Communication speed	12Mbps
Hard disk	40 GB		
I/O connections	CPU, Motor controller & Optical communication boards. LAN, IDE, CAN×2, CCD camera, LED light and 4 motors	Allowable angle for the robot	±6°
		Allowable angle for the receiver in the manhole	±1°
Size	243(L)*90(W)mm	Size	95(W)*75(H)mm

electronics, KANTARO hardware is designed base on modular architecture. Table 5.3 illustrates the specification of KANTARO electronics boards.

5.5.3 KANTARO Sensors

Autonomous sewer robots must include sensors for their own control, navigation and localization, not only those for sewer state assessment and damage detection. In addition, localization is an issue not only for the proper robot control, so that the robot knows where it is, but also for inspection, as detected damages have to be reported with their location. Therefore navigation and localization for the sewage inspection robots, as a whole, can be classified in two main group: "motion-navigation" used for control and robot motion and "damage-navigation" applied for the location of damages in the pipe. The sensors used for motion navigation may overlap with the inspection sensors (e.g. a camera may be used for both motion navigation and damage detection). Motion-navigation sensors, mostly, mounted in front of the robot that it makes

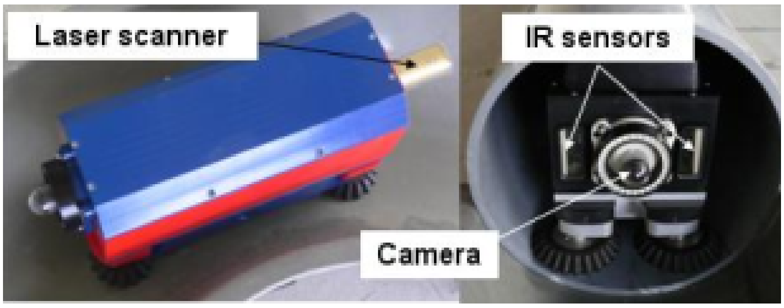
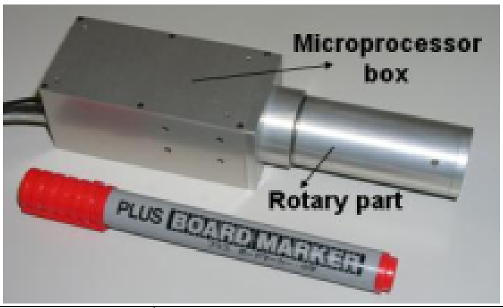


Figure 5.42: First (left side) and second (right side) version of KANTARO. Kantaro's sensor system consists a camera, a laser scanner, a tilt sensor mounted on the mother board and two IR sensors.

complex design to avoid the overlap of their work spaces. KANTARO's sensor system includes an intelligent laser scanner, one fish eye camera, two IR sensors and a tilt sensor. The first two sensors are only used for damage detection and navigation, because KANTARO, including naSIR mechanism, dose not request any kind of sensor for motion-navigation. In this approach we had no constraint for mounting the sensors, mentioned above, into the upper box of KANTARO. Using a tilt sensor mounted on the mother board, and on-board control program, KANTARO is able to automatically correct for tilt in its pose when driving inside a sewer pipe. To avoid driving the robot in a step down more than 10 [cm] and protection from obstacle, two IR sensors are installed in front of robot in two side of the camera. Figure 5.42 illustrates the arrangement of KANTARO sensors. Rotating laser scanner has been developed as a small and intelligent sensor installed in the robot rear to scan radially the inner side of a pipe wall. If the KANTARO moves along the pipe while measuring, the laser beam measures along a spiral on the pipe inside, where the resolution of the spiral depends on the turn rate of the reflection and the speed of robot (Fig. 5.43). To reduce the data processing on the E.B. module, the developed laser scanner is improved to detect the navigational landmark such as manholes, inlets and pipe joints used for damage-navigation, independently, by using a powerful Microprocessor (SH-2) as well as measuring distance and scanning angle, linearized and filtering and modeling data. For realization of a 360 degrees infinitive rotation in laser scanner, we developed a small and special magnet coupling to supply power to rotary part and transmit the laser signal to the Microprocessor box.



Scanning directions	360 degrees
Scanning speed	0-1800 (rpm)
distance range	70-190 (mm)
Accuracy	±1(mm)
Beam radius	0.5 (mm)
Transmission method	Full duplex serial transmission (2Mbps)
Sampling speed	More than 10 KHZ
Measuring signal output	Distance, Scanning angle
Wight	200 g
Size	37×48×166 (mm)
Power	±12V(0.5A) +5V(1A)

Figure 5.43: The newest laser scanner is capable to detect the navigational landmarks, independently with the main computer, as a sensor module.

5.5.4 KANTARO as A Fully Autonomous Sewer Inspection System

In this section, first, we describe how KANTARO can be employed as a fully autonomous robot for finding the pipe damages and fault detection. Second, we will show our approach to make a safe and robust system in point of view of sewer inspection companies as users. KANTARO is capable to detect the candidate faulty images (called feature-images) on-board, by using a fast and simple edge detection program running on its E.B. module. Feature-images may include three different types of image:

- Landmarks (manholes, pipe joints and inlets)
- Faulty images (Fig. 5.45-left)
- Non-faulty images (eg. images including trashes)

When robot detects a feature-image, an autonomous control program will start to decrease the robot speed for saving enough images, up to 5 frames, from feature-image area. Saving the images, directly, is done by ADV202 image compression chip, installed in CPU board, to the hard disk without involving CPU in saving process. At this time, the laser scanner, that has been kept switch off during the normal pipe condition (no feature-image detected by on-board program), will start to extract the possibility of

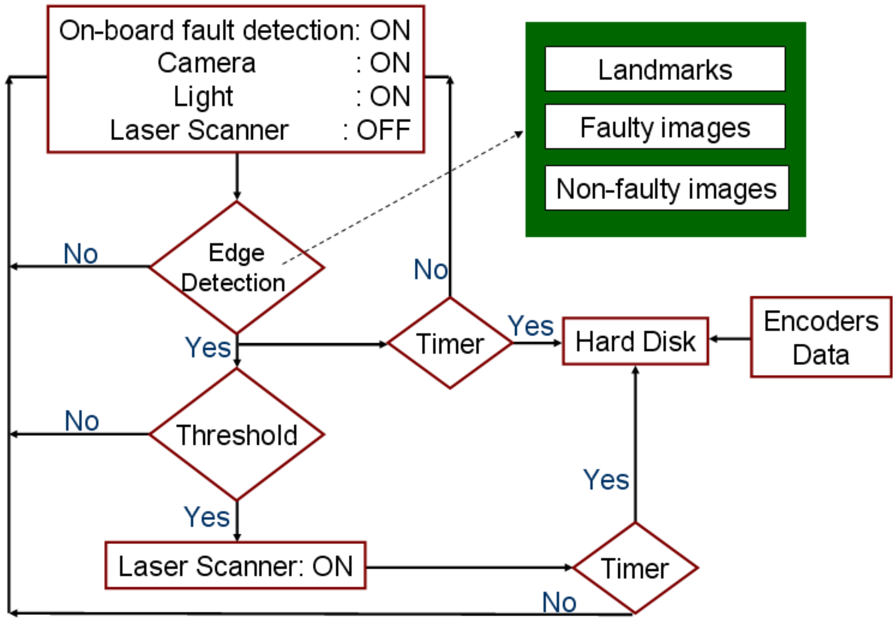


Figure 5.44: The sequence of on-board inspection process.

happened feature fault as a land mark. In case of detection of fault as a land mark, the type of landmark, only as a code, will be saved via CAN interface into the hard disk. These start and stop process of saving data from camera and switch on/off the laser scanner perform a longer inspection process where we consider the capacity of hard disk and energy consumption. In addition, the time, robot speed and encoder data from four DC motors are saved to the hard disk during whole inspection process. Figure 5.44 shows the sequence of on-board inspection process. After the robot is retrieved, all data saved in the robot hard disk will transmit via the LAN interface to the host PC. In this PC, three different programs are applied to extract the real faulty images from the retrieval feature-images and calculate the position of happened fault. First, the feature-images are divided to the landmark images and the faulty-non faulty images by applying the laser scanner data and the time to the images. In the next step, a special fault detection patented algorithm extracts up to 60-70% of the faulty images from the faulty-non faulty images (Fig. 5.45) [55]. Last, the rough position of the faults will be calculated by using the encoder data, robot speed and time. This program has possibility to accept the map data of the sewer network (position of manhole, inlets and pipe joints) and fusion with laser scanner data to decrease the error of wheels slip and more accurate calculation of the happened fault position. After of all, the remain faulty images including the necessary specification will save as a result of inspection process. Figure 5.46 describes the sequence of off-line inspection process.

To make a practical, safe and robust system, we introduced a life-optic-untethered

Nine types of fault
crack
water infiltration
root invasion
pipe break
pipe gap
packing gap
mortar
an alien substance
landslide

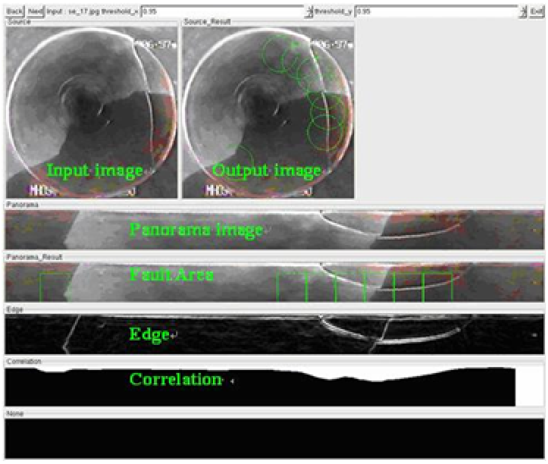


Figure 5.45: Nine different types of fault, possibly happening in the sewer pipe (left side). An example of result of special fault detection patented algorithm applied on a faulty image including a crack (right side).

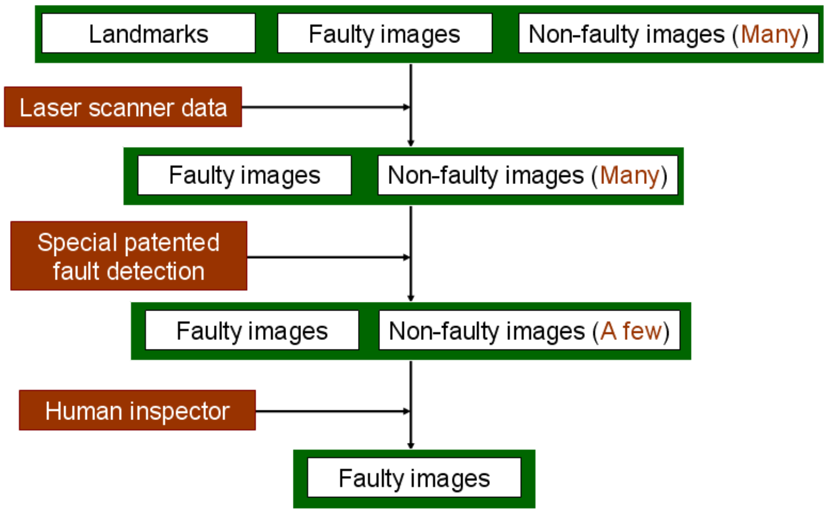


Figure 5.46: The sequence of off-line inspection process.

cable for KANTARO. With this cable that act as a tail for robot, operator can connect the robot to the control units located in out of the manhole via the fiber optic while the robot is driving into the pipe. In this case, operator can observe the condition of the pipe interior and also has possibility to control the robot and use the KANTARO as a semi-autonomous robot for pipe state assessment. Also this cable can be used as a life cable to pull out the robot in the case of stocking it inside of the pipe or power failure. The length of the cable is designed 50 meters as the same length as maximum distance of two manholes (see Fig. 5.47). In this approach, we could solve general skepticism about using fully autonomous systems without a possibility to interfere the

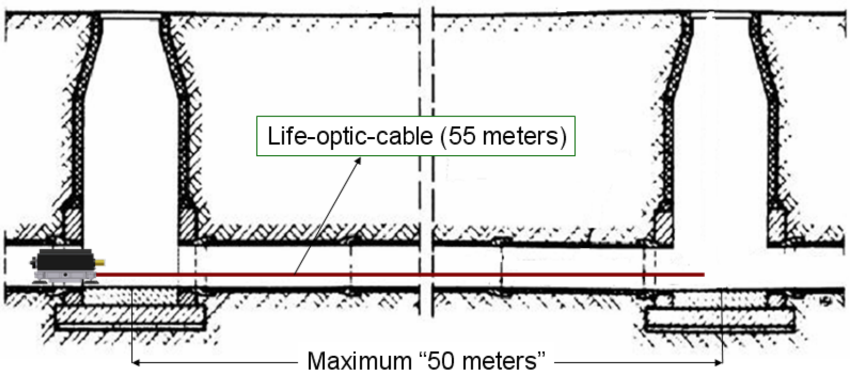


Figure 5.47: KANTARO with the life-optic-untethered cable.

robot control at any time. In addition, the operator can send the basic commands such as a move/stop the robot, turn on/off the light and save/not save data to the hard disk and so on via the optical underground wireless communication module.

5.6 Experimental Results

We evaluated the performance of naSIR mechanism and our sewer inspection robot by driving KANTARO in a sewer test field, in our RRI laboratory, which is made by PVC material with a diameter ranging from 250 to 300 mm. Our test field, including all kind of pipe bends, small steps and also navigational landmarks such as manhole, inlets and pipe joints, can present as a sample of real world sewer network in Japan (Fig. 5.48). naSIR platform (see Fig. 5.37) is able to move in this sewer network up to 4 hours with one battery pack, charged in advance, without any control or stocking in the pipe bends and steps. Also KANTARO, as a whole system, has been successfully employed for autonomous damage navigation and fault detection up time about one hour (400 meters in advance). In addition, we had several chance to drive and test KANTARO in real world sewage pipe network. Figure [cap:Real world test field] shows KANTARO while passing a straight pipe with 250 millimeter in diameter. In this real test field experiment, KANTARO could successfully pass 80 meters pipe network, including 3 manholes and one junction, and perform all task mention in previous section.

5.7 Conclusion

In this chapter we proposed an innovative, fast and robust sewer inspection method by using a passive-active intelligent, fully autonomous, un-tethered robot,called "KANTARO", which fits to the pipes within a diameter range of 200-300 millimeters. KANTARO prototype robot, including a novel passive-active intelligent platform (naSIR

Figure 5.48: Our sewer test field including all kind of pipe bends at RRI laboratory. Two down pictures showed KANTARO when passing a junctions (Left side) and a 90 degree curve (Right side).

Figure 5.49: KANTARO in real world sewage pipe network while passing a manhole.

platform), has a robust movement into the straight pipe and smooth and rapid motion while passes different kinds of pipe bends without need of any intelligence of the controller or sensor reading. In this approach KANTARO does not request any kind of sensor for its motion inside of the pipe. In addition, we developed a small and intelligent 2D laser scanner for detecting of the navigational landmarks such as manholes and pipe joints independently with main computer system and fusion with a fish eye camera, mounted on the KANTARO, used for assessing the pipe state and fault detection. Realization of KANTARO as a fully autonomous, reliable and robust pipe inspection robot has been achieved by designing an architecture based on intelligence at its modules and definition and implementation of a life-optic-untethered cable to make the inspection process easily and safely. To prove that KANTARO is able to use as a commercial product, We still have to perform further experiments in real world sewer pipe network with different in size and state pipe condition. Improving the offline fault detection software to get high accuracy is on the future work.

Chapter 6
Conclusion

Chapter 6

Conclusion

In this thesis the concept of "intelligent mechanical design" is presented to show how a mechanical structure can be designed to have an effect to the robot controllability, simplification and its tasks performance. The description of this concept will lead us to establish the landmarks of the territory of mechanical designing in the form of seven design principles. The design principles, named “Mecha-telligence principles”, provide guidance on how to design autonomous mobile robots mechanics. They incorporate the insights gained in this large design field in a compact and coherent form. Macha-telligence principles guide us in asking the right questions when investigating issues concerning a self-controllable, reliable, realizable, and compatible mechanics for autonomous mobile robots (principle 2). To show how the Mcaha-telligence principles can be applied on the processes of the design of robots mechanics, we proposed a novel methodology, "Mecha-telligence" methodology. Mechanical design in the proposed methodology is done based on preference of classification of the robot specification described by interaction of the robot with its environment and, also, the physical parameters of the robot mechatronics itself (principle 1). In this approach the robot specification is classified to a set of high-level- and low-level-specifications which can be expressed as tasks (desired behavior) and physical parameters of the robot, respectively. In fact the high-level-specification, including the two layers: main and sub layers, is described by considering the robot tasks and its interaction with the environment in which it is used. A low-level-specification may, consequently, consist of a set of layers explaining the physical setup of the robot, its body, sensory, and motor systems.

A main goal in these analyzing process of the robot specification, is that, figure out to a Mono-spec layer (the last layer of low-level-specification) including a simple basic function or selecting a sensor for a single task or behavior. The mechanical design will be started based on an important defined robot mono-spec, and it will be extended to realize the other mono-specs by adding the minimum actuators and sensors to the design (principle 6). In each step of the design process, also, we are trying to come up to the proper solution by considering the robot morphology, design the suitable actuators, applying the description of environmental and physical-morphological constraints, and employing passive mechanisms which have inherent intelligence characteristics (principle 3 and 4) . In this methodology the mechanical design will be finalized by considering the proper and sufficient positioning of sensory-motor system (principle 5) and concept of modularity in robot mechatronics (principle 7).

To prove the validity of proposed method we concentrate on developing of the mechanical structure and devices of three types of autonomous mobile robots used in the three different educational, entertainment and industrial applications. In these three projects we describe, not only, the mechanical design process based on "mechatelligence " principles and methodology, also, the detail design will consider to lead readers to get familiar as much as possible to our vision related to the presented design methodology. Here we, briefly, summarize the results of these three projects which are realized by considering the Mecha-telligence theory in all design, simulation, manufacturing, and assembly processes.

The first project was on developing an autonomous mobile soccer robot which has fully mechatronics modular architecture including a strong ball-kicking device with capability of lifting the ball and a ball-holding mechanism, aiming at getting champion in RoboCup Midsize League. We developed a strong kicking device with capability of shooting (up to 5 [m/s]), lifting (up to 120 [cm]), and holding the ball. One of the specific features of the developed kicking device is that, the ball-kicking and ball-holding are accomplished by only employing a simple DC motor-gearhead and a limit switch. This kicking device, also, has an inherent design characteristic to lift the ball by using the different shape of plates installed on the kicker.

The second challenge was on the design, modeling, simulation and implementation of a series of entertainment robots named "Jumping Joe", exhibited in Aichi Exposition 2005. Jumping Joe robots, artistic and agile robots, can perform several rapid movements such as fast wake up, jumping and somersault. The key point for realization such kinds of rapid movements, is developing two new types of actuators: Inertia Actuators and Cam Charger. Inertia Actuator absorbs mechanical energy by increasing its rotor angular velocity and delivers energy by decreasing its rotor velocity. Inertia Actuator can generate a small internal torque by changing the speed of the rotor and a big internal torque in short time by using a brake to stop the rotor at high speed. Cam Charger including the same mechanism used as a kicking device for RoboCup robot, is designed to fit to the foot shape with capability of. In this case we designed a unique and compact cam including a releasing part to avoid the distribution of the force at the moment of springs energy releasing to the foot structure.

In third project we propose an innovative, fast and robust sewer inspection method by using a passive-active intelligent, fully autonomous, un-tethered robot called KANTARO which fits to the pipes within a diameter range of 200-300 millimeters. KANTARO prototype robot, including a novel passive-active intelligent moving mechanism, can move into the straight pipe and pass different kinds of pipe bends without need to any intelligence of the controller or sensor reading. The proposed method, design the morphological mechanism and sensor less robot will achieved completely based on "mecha-telligence principles and methodology.

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