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HUMAN-ROBOT COOPERATION BASED ON VISUAL COMMUNICATION

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Abstract. *This paper proposes a human-robot cooperative system supported by visual communication. Human-robot cooperation is expected in various fields nowadays in order to raise efficiency, accuracy and safety of work, to name a few, production of goods, logistics, car driving, care of aged people, etc. In the human-robot cooperation, it is desirable that a human takes less part of work; whereas a robot takes a larger role with it. The idea of the present paper is that visual decision making is done by a human rather than a robot. The proposed system goes to a specified remote spot autonomously and performs objects acquisition there by communicating visually with a user. It aims at realizing 'a shopping robot' in near future and expected to be used by disadvantaged shoppers. The proposed system is presented and some experimental results are shown.*
Keywords: Man-machine cooperation, Human-robot cooperation, Visual communication, Human care, Autonomous robots, Depth, Segmentation

1. **Introduction.** Nowadays, in order to realize a higher level of efficiency, accuracy and safety of work, a robot has been introduced in various fields. In particular, a human-robot cooperative system has been taking an important role as it can take account of real-time human intension or desire. One of the final goals of robotics is to realize a fully automatic intelligent robot independent of a human. However, there may still be many kinds of work which need to know the intension/desire of a human to finish the provided work successfully. It is therefore referred to as human-robot cooperation. In this paper, an attention is focused on an acquisition system of remote objects which realizes choice of objects in real time by a remote user employing visual communication.

A number of industrial human-robot cooperative systems have been proposed to date and some of them are put into practical use in factories [1]. The system proposed in this paper is, on the contrary, devoted to a human life. It intends to improve the quality of life (QoL) of those who need some care such as aged people, patients lying in bed, impaired people or even those who are busy with housework including taking care of a baby. The system realizes acquisition of remote objects a user specifies by a mobile robot by the employment of visual communication based on camera images the robot acquires. Similar ideas are proposed [2,3], in which a system is introduced for selecting a book at a remote shelf interactively with a user. However, their systems concentrate only on a book selection and they do not have the idea of appropriate share of the load between a robot and a disadvantaged user such as an aged or a physically impaired person. An autonomous multi-agent system is proposed [4], in which cameras and a PC find an object

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which a human points and a mobile robot conveys it to him/her, but the system requires prior camera calibration and high precision in pointing direction detection. Literature [5] generalizes the objects to be selected. It has weakness in segmenting and finding an object specified by a user in an acquired image, though, because the employed robot performs object segmentation by using template matching of known objects, which will not work well in a cluttered scene. Literature [6] employs an RGB-D camera for segmentation and grasp of an object. However, the entire system is still at a stage under development, as it operates with respect to simpler objects arrangement at a given spot and no robot movement between a user and the spot. Object segmentation [7-10] and grasping [1,11,12] are important issues as well, but they do not have any ideas on visual communication.

Existing human-robot communication systems [13-15] normally employ electronic codes as a communication tool. It will develop further to the communication using languages. On the other hand, exchanging visual information is also useful and important for the communication which includes pattern understanding. However, existent literature neither claims the importance of visual communication, nor proposes such a system employing visual communication. The present paper proposes a way of realizing human-robot visual communication, by which the paper contributes to more exact understanding and reliable cooperation between a human and a robot.

The system proposed in this paper has the following advantages over the existent systems.

(i) No limit in handled objects, only if they can be grasped by an employed robot hand.
(ii) Arbitrary placement with the objects to be grasped. Partial occlusion is allowed.
(iii) Less amount of object recognition is performed by a robot, since recognition and selection of objects are rather done by a user. Hence one can expect steady achievement of the user's desire in object acquisition.

Among the above three advantages, the importance of (iii) should be emphasized. The idea is that object recognition and objects segmentation may be tough work for robot vision in a real environment where appearance changes, occlusion occurs and illumination varies. Hence a human, an expert of pattern recognition, performs the object recognition in place of a robot, which is less good at doing it, in understanding a given scene and choosing one of the objects shown on the display by mutual visual communication. This may realize steady attainment of the intention or desire of the user. The idea also suggests that the system can provide on-site objects selection by a remote user.

It is obvious that food preparation is an important issue along with medical treatment in particular for those who need certain support in a daily life. The paper focuses its attention on the food preparation. The proposed human-robot cooperative system is intended to be employed in the future for disadvantage shoppers.

In the proposed system, a mobile robot moves to a certain spot (a store), takes (buys) some objects (goods) a user wants, and brings them back to him/her. This job is characterized by human-robot cooperation through visual communication via a local area network.

The paper starts by overviewing the problem to be challenged in Section 1. It is followed by the explanation of the proposed human-robot cooperation system in detail in Section 2 and experimental setup and results are presented in Section 3. The proposed system is discussed of its advantages and further issues to be investigated are presented in Section 4. Finally, the paper is concluded in Section 5.

2. Proposed System.

2.1. Overview of the system. The proposed system is composed of a mobile robot, a LAN and a user. The robot is equipped with an RGB-D camera, a 5-DOF manipulator and a PC. Overview of the system is given in Figure 1.

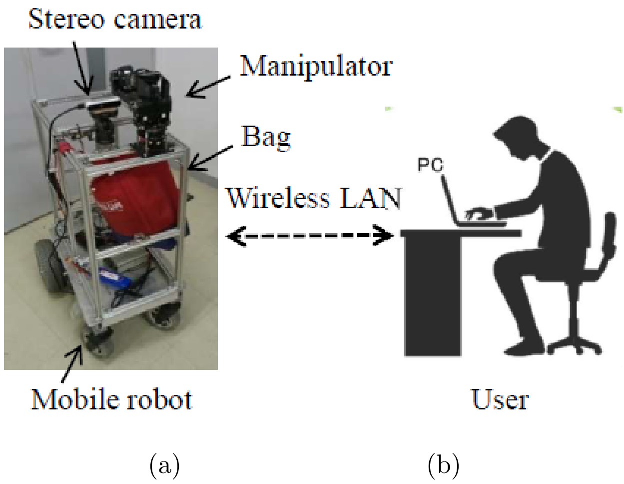


FIGURE 1. Experimental system: (a) Robot; (b) user in a distant room

The outline of the procedure is explained referring to a diagram shown in Figure 2. 1) A user tells a destination to a robot where his/her desired objects exist. 2) The robot then autonomously travels to the place. 3) It transfers the images of the objects there to the PC of the user via a wireless LAN. The user chooses an object by touching it on a display. Then its coordinates are transmitted to the robot as a clue of the object. Taking the clue into account, the robot gets the object. 4) It brings the object back to the user.

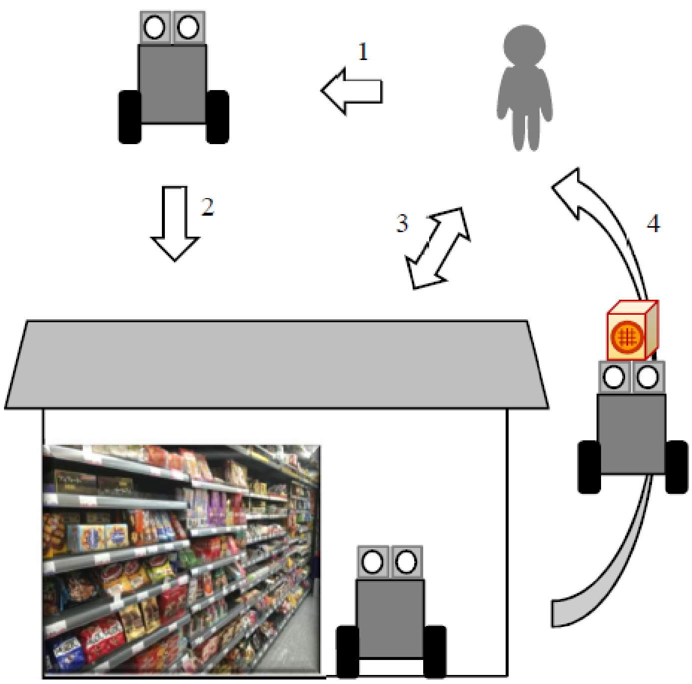


FIGURE 2. Diagram of the procedure for the human-robot cooperation

In the above procedure, transferring objects' images from the robot to the user, user's selection of a particular object on a display and transmission of its coordinates to the robot are referred to as visual communication. The entire procedure is general as well as natural similar to human communication and is formulated by a sequence of respective procedures: $1 \to 2 \to 3 \to 4$. The flow of the procedure is described in detail in Figure 3.

The user is concerned only with designating a destination and selecting objects. The robot is, on the other hand, expected to execute all other procedures such as traveling to the destination and finding product display shelves by itself, so that the user may not be involved in robot control. Hence, it is a system that the robot delivers what a user wants with the minimal burden put on the user.

2.2. **Flow of the cooperation.** As shown in Figure 3, the overall flow is composed of a flow w.r.t. a robot and a flow w.r.t. a user. They are explained in the following. Each procedure is referred to by R# and U# indicated in Figure 3.

U1: The entire procedure starts by a user (User) specifying a robot (Robot) the spot it should go.

R1: Robot judges if it has got the information on a spot.

R2: If yes, it moves to the spot. Otherwise, it waits until a spot is specified by User.

R3: Robot moves to a shelf at the spot and pans a camera to get an image of objects on the shelf. Note that objects are on a store shelf as the present study assumes the spot is a shop like a supermarket.

R4: Robot sends the image to User through wireless LAN.

U2: User judges if there is an object which User wants in the sent image. **U3:** If yes, User specifies it and sends 'Y' to Robot: Actually, User touches inside of the object on the screen of User's PC and the image coordinates of the touched point, say P, is sent to Robot as the sign 'Y'. **U4:** If not, User sends 'N' to Robot and returns to U2 via label:2. It is noted that NA (Not Applicable) means that User/Robot waits until respective signals are sent from a partner.

R5: Robot judges Y or N w.r.t. User's reply. If 'N', the procedure returns to R3 via label:1. If 'Y', it proceeds to step R6.

R6: The average distance d_{ave} is calculated in an n_c by n_c square ($n_c = 15$ pixels in the performed experiment) centered at point P. If $d_{\text{ave}} \geq d_{\text{th}}$ (d_{th} is a threshold defined in advance: $d_{\text{th}} = 560$ mm in the experiment), Robot moves a certain distance forward. This procedure is repeated and, once $d_{\text{ave}} < d_{\text{th}}$ holds, it begins object segmentation around P. The segmentation is done by growing the object region originated from P. The initial object region is an n_{init} by n_{init} square ($n_{\text{init}} = 15$ pixels in the experiment) centered at P. The resultant object region is enclosed by a rectangle and is sent to User. The condition $d_{\text{ave}} < d_{\text{th}}$ means that Robot is within the area where it can grasp the object.

U5: User judges if the segmentation is correct. **U6:** If yes, User sends 'Y' to Robot by touching inside of the rectangle. **U7:** Otherwise User sends 'N' by touching outside of the rectangle and returns to U2 via label:2.

R7: Robot judges Y or N w.r.t. User's reply. If 'N', the procedure returns to R3 via label:1. **R8:** If 'Y', Robot acquires the object from the shelf by grasping it by its hand and puts it in a bag.

U8: If User has a further request on interested objects, User sends 'Y' to Robot via **U9** and the procedure returns to U2 via label:2. Otherwise the procedure ends.

R9: Robot examines if there is a further request from User. If 'Y', it returns to R3 via label:1. **R10:** If 'N', Robot conveys the collected objects to User.

2.3. **Object segmentation [6].** As stated above in R6, segmentation of a particular object is done by region growing on an image. The employed RGB-D stereo camera

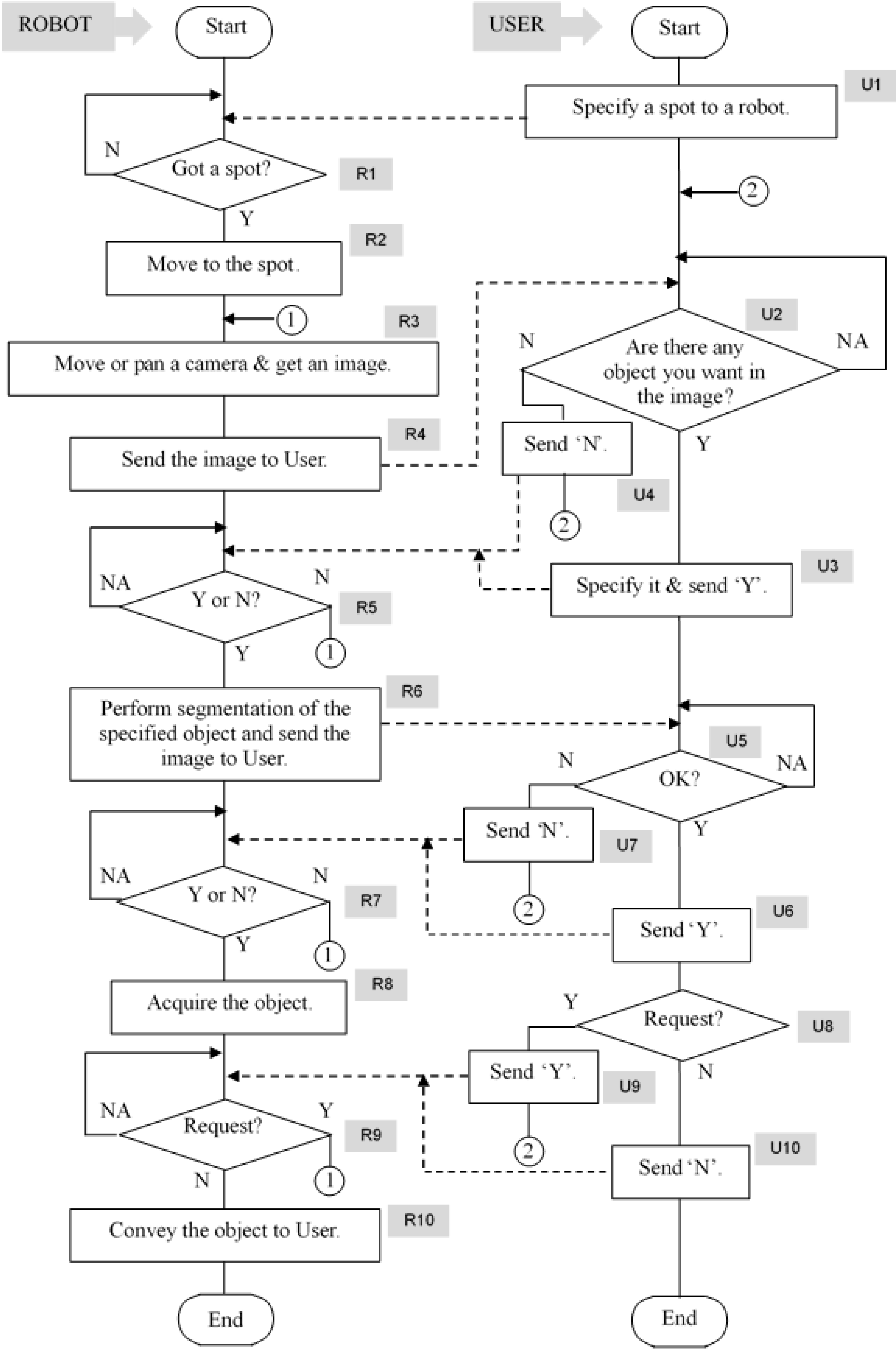


FIGURE 3. Detailed flow of the procedure for the human-robot cooperation

provides a depth image, from which surface normals are calculated at every pixel, yielding a 2.5-D image. The region growing algorithm expands a region by including neighbor pixels having normals with similar direction within a certain tolerance. Since discontinuity of the direction occurs at the boundary of an object, the algorithm stops there. This applies to both plain and smoothly curved surfaces.

Obviously, object segmentation employing depth information is advantageous over other methods in image processing. In a practical situation, many objects have picturesque surfaces often with letters. Depth can be employed in the segmentation of such objects indifferent to annoying surface texture.

The present algorithm separates only a single face from an object like a box-shaped object having some faces. The present system expects that User specifies a face on an object with the largest area, which is informative for grasping it. This will further be improved by User touching all the visible faces of an object, though. Robot can then obtain a better clue on a whole shape of the object.

2.4. **Realizing the visual communication.** The visual communication between a human and a robot is realized by the employment of a graphic user interface.

FIGURE 4. Developed graphic user interface for human-robot communication: The screen of a PC is separated into 6 colored zones.

The developed graphic user interface is shown in Figure 4. The display is separated into 6 zones in the figure. They are explained in the following.

$\mathbf{Z_o}$**:** Observation, choice and confirmation zone. The scene in front of the robot camera is displayed.

An object is chosen and segmentation result is confirmed there.

$\mathbf{Z_l}$**:** Turn left zone. The camera turns some degrees to the left.

$\mathbf{Z_r}$**:** Turn right zone. The camera turns some degrees to the right.

$\mathbf{Z_b}$**:** Move back zone. The robot moves back a certain distance.

$\mathbf{Z_s}$**:** Stop zone. The robot can be stopped by a user, when necessary.

$\mathbf{Z_{ret}}$**:** Return zone. User can order the robot to return to him/her.

As explained above, object selection is done at Z_o. Zones Z_l and Z_r are for fine control of the robot orientation and position. In the developed system, this control is introduced in place of Robot's autonomous movement for simplicity. Z_{ret} is for ending the job. User touches this zone to send 'N' to Robot at U10 in Figure 3. Z_s is used for emergency stop.

2.5. **Object acquisition.** To get an object on a shelf by a robot hand, its position in the 3-D space needs to be calculated. Let us denote the centroid pixel of the rectangle enclosing the obtained object region by $\boldsymbol{p}_c(x_c, y_c)$, and $\boldsymbol{P}_c$ in the 3-D space. Let us also consider an n_p by n_p ($n_p = 5$ pixels in the experiment) square S centered at $\boldsymbol{p}_c$ and denote the 3-D position of a pixel $\boldsymbol{p}(x, y)$ in S by $\boldsymbol{P}(X, Y, Z)$. Then the average position $\bar{\boldsymbol{P}}\left(\bar{X}, \bar{Y}, \bar{Z}\right)$ of the pixels in S in the 3-D space is computed by

$$\begin{gathered} \bar{\boldsymbol{P}}\left(\bar{X}, \bar{Y}, \bar{Z}\right) = ave_{(x,y)\in S}\left\{\boldsymbol{P}(X, Y, Z)\right\} \\ X = \frac{x - x_c}{f} Z, \quad Y = \frac{y - y_c}{f} Z \end{gathered} \tag{1}$$

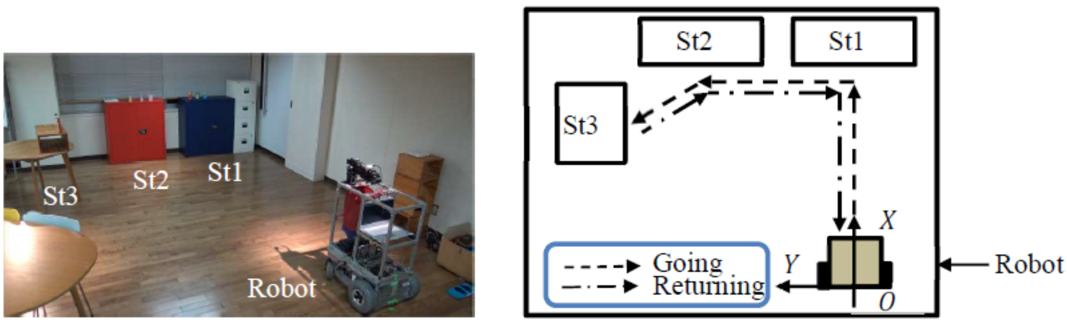
Here *ave* signifies averaging operation and f is a focal length of a camera lens described by the number of pixels.

Since $\bar{\boldsymbol{P}}\left(\bar{X}, \bar{Y}, \bar{Z}\right)$ is described in the camera coordinate system, it is transformed into a robot coordinate system by the employment of a transform matrix, yielding the position, $\bar{\boldsymbol{P}}_R$.

2.6. **Robot navigation.** Robot navigation to the destination and to the User's place is almost automated except for fine adjustment in front of a shelf at the specified spot by touch of Z_l and/or Z_r (and Z_b when necessary) by User. Touch of Z_b is also an instruction to Robot navigation. Navigation between User's place and the specified spot is simplified in the present system, as the main objective of the present paper is to show effectiveness of User-robot communication and cooperation. The navigation to a spot is done by memorizing the locations at every constant distance on the way. The way back navigation is done by tracing the memorized locations. Assuming that Robot is modeled by independent bi-wheel driving, computation of its ego-location is done employing wheel odometry and extended Kalman filter.

3. Experimental Results.

3.1. **Experimental setup.** An experiment is performed in a lab where some objects are arranged on book shelves as simple simulation of real shop shelves. The employed mobile robot is shown in Figure 5(a) and User does necessary manipulation in an adjacent room. Robot is equipped with a stereo camera (Intel$^{\mathrm{R}}$: RealSense D415), a 5-axial manipulator (RT Corporation: Dynamixel Arm) and a bag to keep acquired objects. They are all tightened to a case on a mobile robot (Okatech: MECBOT#001). A PC is placed at the back of the case as seen in Figure 5(a). Robot's PC and the PC of User are connected mutually via wireless LAN. The specifications of the PC on Robot and of User are as follows; OS: Windows 8.1 64 bit, CPU: Core i7-4510U (2.00 GHz), RAM: 8.00 G, and OS: Windows 7 32 bit, CPU: Core i5-3320M (2.60 GHz), RAM: 4.00 GB, respectively.



(a) (b)

FIGURE 5. Deployment of Robot and stands in the preliminary experiment: (a) Robot and 3 stands (abbr., Stj, $j = 1, 2, 3$); (b) going and returning trajectory of Robot

3.2. **Result of the preliminary experiment.** In order to examine object acquisition and exactness of movement of Robot, a preliminary experiment was performed. As shown in Figure 5(a), there are three stands in a room and three objects (snacks in a cylindrical box) are placed separate in a row on each of them. The stands are approximately apart 1 to 3 meters away from each other and Robot is initially apart approximately 5 meters away from the stands. The pass of Robot is shown in Figure 5(b). It travels from the origin of the XYZ world coordinate system to Stand_1, _2 and _3 in this order following the broken lines. It takes one object at each stand by the visual communication with User. Then it returns to the original spot by following the one-dot chain lines. Since the main objective of the present paper is to show human-robot cooperation in remote objects acquisition, the travel of Robot to destinations is controlled manually by User for simplicity, whereas it returns to the original spot autonomously by use of memorized going forth passes.

This scenario was tried 5 times and the result was evaluated by (i) if exact objects were acquired, and (ii) the distance errors between the original and the final position after the return. The result is given in Table 1.

Table 1. Result of the preliminary experiment

Trial	Distance (m)	Stand_1	Stand_2	Stand_3
1	0.33	S	S	F
2	0.15	S	S	S
3	0.25	S	S	S
4	0.62	S	S	S
5	0.33	S	S	S
Average	0.34	–	–	–

S: success, F: failure

As shown in Table 1, Robot got objects successfully in all the stands and all the 5 trials except for Trial 1-Stand_3, in which case the manipulator contacted the object concerned and it fell there. The positional error was 34 cm in average. This may be acceptable in a 5 m by 5 m space.

3.3. **Result of the main experiment.** An object acquisition experiment was done in a more cluttered objects environment. The scene employed in this experiment is shown in Figure 6(a). Two shelves are placed and many objects are put on the shelves whose images are enlarged in Figure 6(b). Most of the objects are boxed snacks whose shape does not change. One deformable object H, snacks in a bag, is put on Shelf_2. In this situation, Robot first travels to Shelf_1 and takes objects D, E and F by the visual communication with User. Then it moves to Shelf_2 and takes objects G and H by the communication. Having put all the objects into a bag, it finally returns to its original spot. The trajectories of going and returning way are depicted in Figure 6(c). The performance of Robot is shown in Table 2. As is in the table, object acquisition was all successful along with a positional error 10 cm smaller than the average error in the preliminary experiment.

Table 2. Result of the experiment

Distance (m)	Object				
	D	E	F	G	H
0.10	S	S	S	S	S

S: success

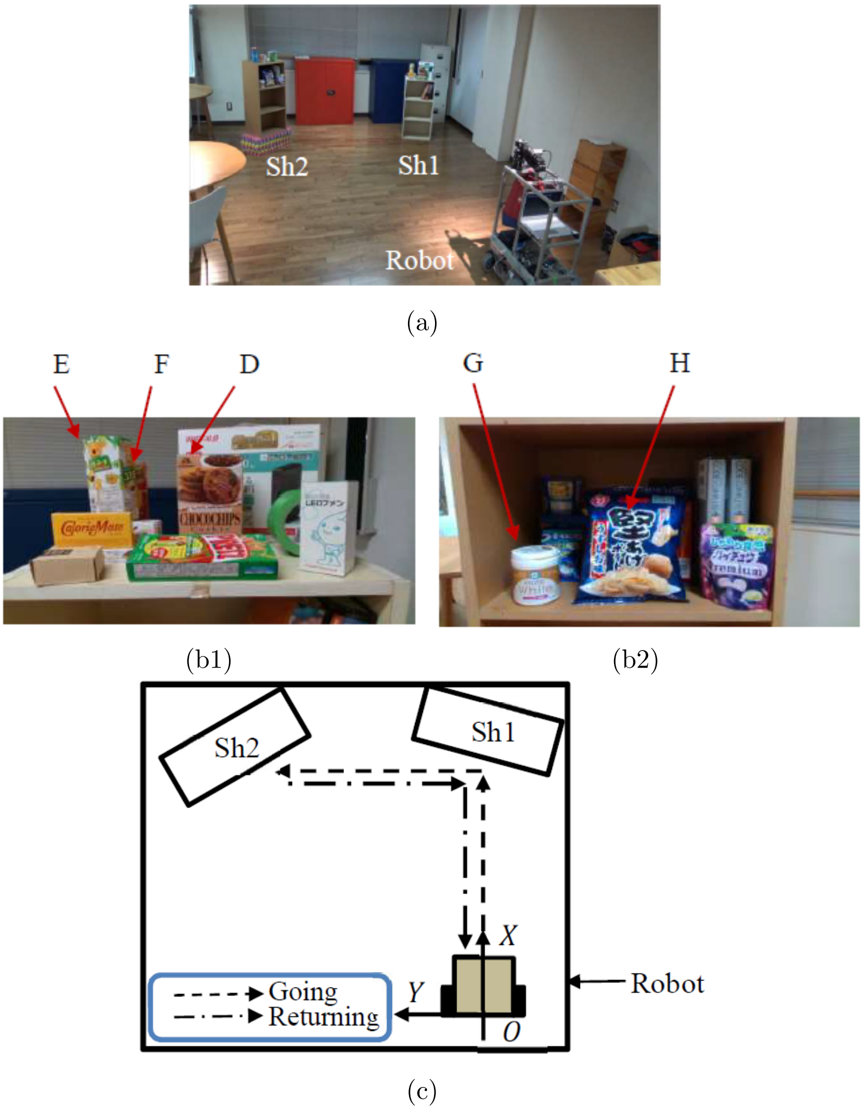


FIGURE 6. Deployment of Robot and objects (shelves) in the experiment: (a) Robot and 2 shelves (abbr., Shk, $k = 1, 2$), (b1) objects on Sh1, (b2) objects on Sh2, (c) going and returning trajectory of Robot

The experiment is videotaped and some sampled shots are shown in Figure 7. The movement and the work Robot does are explained in the following.

(a) Robot moves to Shelf_1. (b) It stops in front of Shelf_1. (c) It grasps object D according to User's request. (d) Object D is put into a bag. (e) Robot grasps object E according to User's request to put it in the bag. (f) It grasps object F according to User's request to put it in the bag. (g) Robot moves to Shelf_2. (h) It stops in front of Shelf_2. (i) It grasps object G according to User's request and puts it in the bag. (j) It grasps object H according to User's request and puts it in the bag. (k) Robot returns autonomously by tracking the way it came. (l) It stops at the original spot.

4. **Discussion.** This paper proposed a method of remote objects acquisition by human-robot cooperation employing visual communication. The performance of the method was shown by experiment and satisfactory results were obtained in a laboratory environment.

Visual communication is important in transferring an idea concerning pattern (including texture) between a human and a robot (or even among humans), since it is direct and

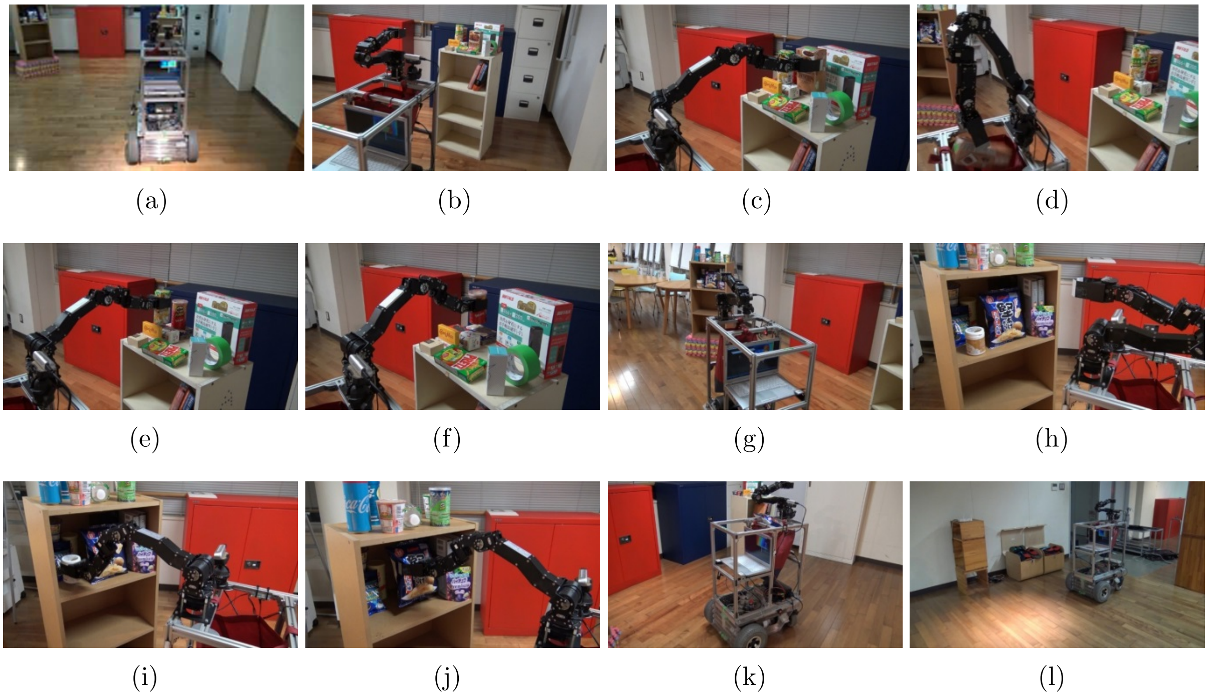


FIGURE 7. Experimental result

therefore more exact in pattern understanding compared to the communication employing electronic codes or languages.

A mobile robot for human aid may have three main types: (i) a fully autonomous, (ii) a master-slave and (iii) a cooperative robot. Obviously (i) is the best for routine work. However, there is often a case in which the robot needs asking a decision of a human. This necessitates communication with a human. Since one of the main reasons of employing a robot in a human life is to obtain free time for a human to do some other activities, (ii) had better be avoided, because a human must control a robot all the time during it is in action. Then (iii) may give the best solution on condition that the robot is autonomous.

The idea of the proposed method is division of roles: decision making by a human and object handling and conveyance by a robot. In particular, the former is important. An object can be specified in advance by a human, or there is a case in which a human selects a particular object by seeing the transferred images and comparing it with other similar objects. The proposed division of roles is effective in a realistic sense.

Furthermore, the reason why objects should be selected cooperatively is that general objects recognition by a machine is difficult in a real world environment because of appearance change in the 3-D space, occlusion, lighting, etc., other than that there are countless number of objects in one's surroundings. On the other hand, object recognition is easy for a human. A human can even find small differences among similar objects. It is therefore rational to realize human-robot cooperation for a practical robot care system which includes object recognition. This is realized in the proposed system by the employment of visual communication between a robot and a human through a wireless LAN. Extension of the present system to the system employing Internet will be done in near future.

A wheel-type mobile robot was employed in the performed experiment. It is enough for developing a practical system based on the proposed idea, since it is stable and well controllable. In future, a humanoid will take place of a mobile robot particularly in human-robot cooperation because of its high compatibility with a human, although it is still under development.

In the performed experiment, travel control of the employed robot is still in a basic stage and its travel distance is not long enough to be used outdoors. We have already developed a mobile robot which travels a long distance in the campus of KIT-Tobata [16] while avoiding obstacles. The developed robot control knowledge will be combined to the present system. Spot recognition by a robot, such as finding a particular store, is a further issue to be developed. Putting emphasis on map understanding and character recognition may help solve this issue. These improvements will lead to realizing a practical remote objects acquisition system outdoors.

Some other constraints on realizing a practical system include the followings. One is the communication speed in transferring visual information. Visual communication will be done mainly while moving to/from a specified spot and while finding and choosing goods at a spot. Since a large amount of visual data will be transferred, communication speed should be fast enough to realize real-time operation. This has, however, been solved gradually by the recent development of Internet technology. The other constraint is the power of the manipulator on a mobile robot. A manipulator installed on a laboratory-base mobile robot can grasp only a very light object, say, up to 500 g. This will not be enough for a practical use. One must expect the development of a more powerful and smaller size manipulator.

Among various sorts and shapes of products on various kinds of product display shelves in various forms of rooms, the performed experiments employed fewer kinds of products, some popular boxed snacks, on a standard shelf in a lab room. Although the configuration of the experiment is rather simple, emphasis is put on, in this paper, to propose the idea of human-robot visual communication and to claim its importance in the communication which concerns visual pattern. The study is planned to proceed to the next stage, i.e., on-site demonstration experiment in the near future.

The proposed system intends at present to be used by those who find difficulty in going out for shopping, called disadvantage shoppers, such as patients, disabled or elderly people, and busy stay-at-home mom/dad. Its application fields may, however, be broad, as there may be various kinds of communication and decision making employing visual information.

5. **Conclusion.** A human-robot cooperative system based on visual communication was proposed and its performance was shown experimentally. The importance of visual communication between a human and a robot was emphasized in understanding human thought related to pattern understanding or object recognition. Human-robot cooperation is useful in various activities in a human daily life. Visual communication will enrich the cooperation in many ways.

The study needs to strengthen autonomous mobility of a used robot and to move into a field trial in near future in order to realize a practical robot system.

Application to remote goods acquisition for disadvantage shoppers is our present concern. In future, the proposed system will further be employed in various fields in which a robot alone finds difficulty in judgment.

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