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Teleoperation of a Multi-Purpose Robot over the Internet Using Augmented Reality

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Abstract: Bilateral teleoperation using augmented reality is proposed for a multi-purpose robot called SpiderBot-II that is an indoor-installed wire-driven parallel manipulator. It is intended to be used for various applications, including in-house rehabilitation training and daily life assistance such as walking assistance and health monitoring, especially for the elderly or the handicapped that spends most of time at home. Through the teleoperation over the Internet, a therapist or an attendant in a remote site can give help to the physically disabled by directly manipulating the robot. For easy recognition of the obstacle, predefined markers are attached to each obstacle in the workspace. For better teleoperation, moreover, reaction force between obstacles and the end-effector, which is calculated using force field, is given to a remote operator and this enables the operator to perform the teleoperation more effectively. Force field, which is proportional to proximity between obstacles and the end-effector, is generated to facilitate the obstacle avoidance and visually augmented on the operator's screen for better recognition of obstacles.

Keywords: Teleoperation, Wire-driven Parallel Mechanism, Augmented Reality, Walking Assistance, Haptic Feedback

1. INTRODUCTION

With the increase of the number of people who have to stay in their home or medical facilities, robotic systems which can be used for indoor activity assistances, such as walking assistance and rehabilitation, have become one of the major research areas. Many efforts have been made on the research of walking support and rehabilitation systems. For example, Care-O-bot [1] provided an intelligent walking aid and it could fetch and carry objects in home environments like a mobile service robot. SmartCane [2] which was based on a cane configuration with a skid-steer drive was a rehabilitation robotic system which was implemented to assist the elderly living independently. These systems were active walking support systems which use human power to move them. When the elderly or the disabled cannot easily load their body on the robot or avoid obstacles, performance of these systems is limited. Also, RT Walker [3] can be categorized into a passive type walking support system. The passive walking support system which uses servo motors to control the motion is not powerful facilities because they are dependent on their batteries capacity. On the other hand, SpiderBot-II [9], which is based on a wire-driven parallel mechanism, combines active and passive walking support capabilities. Since the system is driven by flexible wires, not by rigid links, it can be said that the system is inherently safer than the robots with serial rigid links and this is one of the crucial characteristics which should be considered in human-robot interactions. Also the payload of the system is much larger than the serial robots. So, it can be said that the system we are dealing with has many potential applications in indoor activity assistance.

With the easy access to the high speed Internet, teleoperation systems can be constructed more conveniently ever before and the use of a remote system from all places where the Internet is available is attracting many people. In this paper, we discuss the teleoperation for an in-house multi-purpose robot over the Internet. The robot is, among many potential applications, used for the walking assistance for the elderly or the low-extremity handicapped and can be manipulated by a physical therapist or an attendant at remote site. Bilateral teleoperation approach to rehabilitation system over the Internet was presented in [4] and [5]. For better teleoperation, Dejong et al. proposed teleoperation control using captured images at the master operator and virtual surface [6]. However it is difficult to avoid obstacles depending on only image stream. Although captured 2D image may be utilized to improve a user's cognition of workspace, to recognize real 3D workspace is difficult for the user.

In this paper, we proposed bilateral teleportation based on force field which prevents the collision between the end-effector and the obstacle. For obstacle avoidance, we utilize low cost web-cameras and ARToolKitPlus [11] to realize the vision based marker tracking. With vision based marker tracking, we can easily acquire position and orientation of the obstacles to which AR markers are attached. In this approach, we pre-registered the name and dimension of specific obstacle with AR marker's ID. The force field is automatically generated by using pre-registered information. For example, when the distance between the end-effector and an obstacle is located in close proximity, the force field generates reaction force and transmits to the remote operator. Thus, the remote operator grabbing a haptic device [10] can feel reaction force with respect to transmitted force information from the local site. Therefore, our system may enhance the walking support over the Internet and facilitate manipulation of the SpiderBot-II with avoiding distributed obstacle to the remote operator.

This paper is organized in the following manner. In

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section 2, we describe an overview of the proposed system configurations. Obstacle detection and reaction force generation are described in section 3. In section 4 we discuss bilateral teleoperation control over the Internet. The experimental results are presented in section 5. Finally, in section 6, we conclude this paper and discuss future work.

2. SYSTEM CONFIGURATION

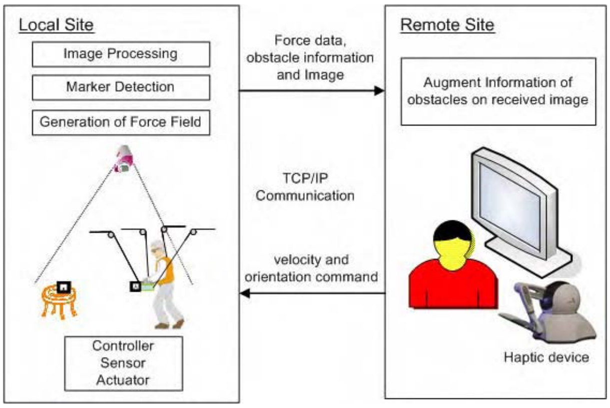


Fig. 1 Teleoperation of the SpiderBot-II in walking assistance scenario.

The proposed teleoperation system of the SpiderBot-II over the Internet using augmented reality is mainly divided into two parts: local and remote site. As shown in Fig. 1, in the local site, there are SpiderBot-II control system and obstacle avoidance method by using augmented reality, in other word marker tracking. Each AR marker has the pre-registered obstacle's information such as name and physical dimension. With pre-registered obstacle's information, force field around the obstacle is automatically created and utilized for computing reaction force. In order to detect AR markers that are attached to each obstacle and the end-effector, the web-camera located at the ceiling is used ARToolKitPlus [11] is utilized to process the captured image sequence and detect the position and orientation of markers. With AR marker, relative position and orientation between the camera and each marker is calculated around 30 Hz, and this information is used to determine whether the end-effector is close to any obstacle. If the end-effector is located in force field, reaction force is computed and then transmitted to the remote operator.

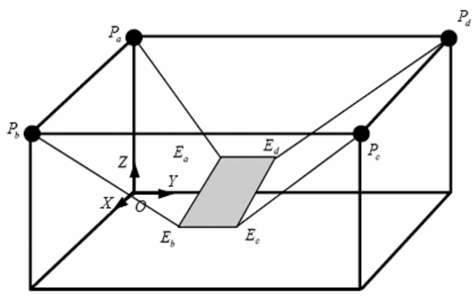


Fig. 2 SpiderBot-II is driven by four wires. Each wire is connected at the end-effector and the corner of ceiling.

In Fig. 2, SpiderBot-II, which is in local site, is an incompletely restrained system, which means that the position and orientation of the end-effector are not determined only by wire lengths. Design, kinematics and control of the system can be found in [7] and [8].

In the remote site, a haptic device with 3 DOFs (Phantom Omni [10]) is used as an input device as well as an output device in the bilateral control of SpiderBot-II. With this haptic device, a user in the remote site can feel a reaction force. With reaction force from the haptic device, a remote operator can recognize whether the end-effector is close to an obstacle. As an input device, the haptic device can be used to generate velocity and orientation command inputs to the SpiderBot-II at local site. On remote site, obstacle's information such as name and force field are visually augmented on the received image at the operator's screen. Data communication is achieved through the TCP/IP protocols.

3. OBSTACLE DETECTION AND REACTION FORCE GENERATION

3.1 Marker detection and acquisition of position and orientation

For Obstacle avoidance and remote control through the haptic interaction, both an obstacle and the end-effector information including position and orientation are needed. To acquire position and orientation of the obstacle and the end-effector, we used the vision-based tracking method which is provided with ARToolKitPlus that allows developers to include vision-based marker tracking in their application and augment their virtual information on the real environment. ARToolKitPlus is based on fiducial method which determines geometric relations by matching a known virtual information and image frame around 30Hz processing rate. In our system, we attached a fiducial marker at the end-effector and obstacles in order to compute relative position between them. However, lighting condition has a significant effect on the sensitivity of marker detection. To overcome this problem, we have applied an adaptive threshold method to ensure robust marker detection. The adaptive threshold method can be written as Eq. (1).

$$V_{threshold} = \frac{\sum Y_i}{Number\ of\ pixles} \tag{1}$$

$$where\ Y_i = 0.299R_i + 0.587G_i + 0.114B_i$$

Y_i is calculated by converting RGB color space to YUV color space. The average of Y_i is used to generate binary images to detect marker in real time. However, in order to reduce the computing burden, we only check some of the pixels. As can be seen in Fig. 3, ten horizontal lines and ten vertical lines are selected from each captured image and only these lines are used to calculate the adaptive threshold level. We found that even the small numbers of pixels were used, the adaptive threshold method resulted in better marker detection than compared when no adaptive threshold method was used.

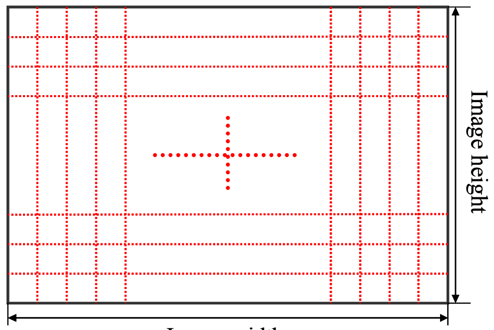


Fig. 3 Inspection grid in the captured image to compute the adaptive threshold.

After this step, the position and orientation of a marker are extracted from the 4×4 marker transformation matrix containing rotational and translational information as shown in Eq. (2).

$$\mathbf{T} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & T_1 \\ R_{21} & R_{22} & R_{23} & T_2 \\ R_{31} & R_{32} & R_{33} & T_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} \quad (2)$$

where R and T indicate rotation matrix and translation matrix of each marker, respectively. With marker's transformation matrix, we can compute the position and orientation (roll, pitch and yaw angle) of a marker with respect to a camera. Orientation matrix is given by Eq. (3).

$$R_{3\times3} = R_{z,\phi} R_{y,\theta} R_{x,\Psi} = \begin{bmatrix} C_\phi C_\theta & -S_\phi C_\Psi + C_\phi S_\theta S_\Psi & S_\phi S_\Psi + C_\phi S_\theta C_\Psi \\ S_\phi C_\theta & C_\phi C_\Psi + S_\phi S_\theta S_\Psi & -C_\phi S_\Psi + S_\phi S_\theta C_\Psi \\ -S_\theta & C_\theta S_\Psi & C_\theta C_\Psi \end{bmatrix} \quad (3)$$

where C and S represent cosine and sine respectively. Each roll, pitch, and yaw angle can be calculated by Eq. (4).

$$\phi = \sin^{-1}\frac{R_{21}}{\cos\theta}, \theta = -\sin^{-1}(R_{31}), \Psi = \sin^{-1}\frac{R_{32}}{\cos\theta} \quad (4)$$

By marker detection, we can easily find the position of the end-effector and an obstacle. In addition, position and orientation are determined by Eqs. (2) - (4) are utilized for computing force field.

3.2 Force field generation and computation of force

For obstacle avoidance, we generate force field around the obstacle. In this process, we assume that information of each obstacle is pre-registered. The registered information of each obstacle contains obstacle's name, dimension in real space, AR marker number and the number of force field layers. This information is stored in obstacle's database at local site. When markers are detected, the force field layers are automatically generated by obstacle's dimension and layer's number as shown in Fig. 4. In this case, the number of force field layer is 8 and layers are created around a chair. With marker position and orientation information, force layers can move or rotate with respect to movement of the chair. Computing reaction force based on the force field layers is determined by location of the end-effector in the layers. If the end-effector penetrates into force layer of a specific obstacle, the reaction force is computed by multiplying penetration depth by weight factor of each force layer. An advantage of force computation based on field layers is that it can provide different reaction force according to proximity between the end-effector and the obstacle. This method ensures that the user may be aware of proximity between the end-effector and the obstacle when the user controls the SpiderBot-II from a remote site. Fig. 4 shows a schematic representation of force field.

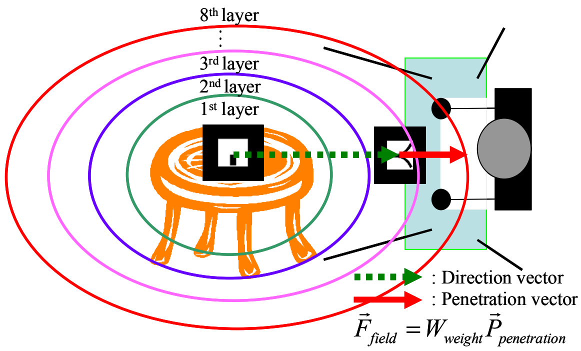


Fig. 4 Schematic representation of reaction force generation.

The algorithm for computation of reaction force is shown in Fig. 5.

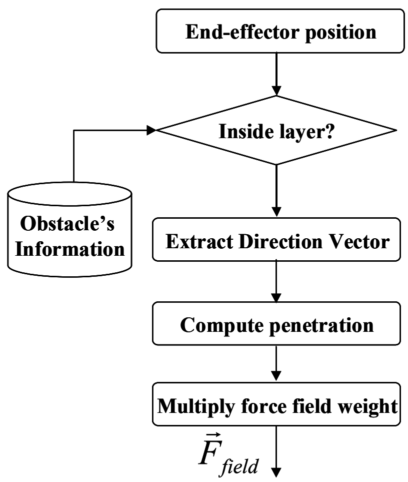


Fig. 5 Sequential stage for generating reaction force based on the force field.

At the first step, the end-effector's position acquired by marker detection is used to decide whether the end-effector is in force field layers. Force field layers are not only generated according to obstacle's dimension, but also created around the obstacle's boundary as shown in Fig. 4. As the next step, the direction vector which is from an obstacle to an end-effector is determined. Then penetration vector is calculated by using outermost layer and end-effector's position. After determination of penetration vector, reaction force based on the force field is computed by multiplying weight factor of each field by penetration vector as following Eq. (5).

$$\vec{F}_{field} = W_{weight}\vec{P}_{penetration}$$
$$W_{weight} = \left(N_l / N_{il}\right) e^{-M_d} \tag{5}$$

where M_d represents magnitude of directional vector, and N_l and N_{il} represent the number of layer and layer's number containing the end-effector, respectively. An exponential function in calculating weight factor plays a key role in producing smooth interaction force. If the weight factor is constant, force discontinuity can be occurred at each border between layers. Therefore, we devised smooth weight factor by utilizing exponential function.

With Eq. (5), reaction force based on the force field is calculated and is utilized to help a remote user to avoid the obstacles in the workspace. A remote user can feel reaction force augmented around the obstacle and this reaction force is important in preventing collision between the end-effector and obstacles.

4. BILATERAL CONTROL

The local site communicates with the remote site through Internet. From the local site, force data and obstacle information are sent to the remote site, and from the remote site, the velocity and orientation command to control the robot are sent to the local site. For this bilateral control, we use the TCP/IP protocol with handshaking. A transmission occurs at the beginning of a session between communicating computers. The handshaking ensures that the two remote computers agree on how the transmission will proceed. The communication data contains reaction force data, control command and obstacle's information (name and force field). Each dataset is not only packed in one packet, but is transmitted by a role of handshake. Fig. 6 shows the data communication sequences with handshaking methods as well as communication dataset.

At the beginning of a communication session, the local site requests remote site to send motion command of the SpiderBot-II. If there are updated control commands, the remote site packs three-axis velocity and orientation commands in one packet and transmits this packet to the local site. After unpacking stage on local site, control commands are used for moving the SpiderBot-II. At the same time, the local site sends a signal of acceptance and acknowledgement to the remote site. After receiving acceptance, the remote site request reaction force data and obstacle's information to the local site. If there are updated forces and obstacle's information that are calculated by marker detection and force field, the local site transmits this information to the remote site. If there is no update, the local site just transmits empty packet. After receiving that information, the remote site sends acceptance. In this sequence, both packing and unpacking data are achieved by the same way as described above. In the case of image transmission, an image sequence is streamed from the local to remote site. This procedure is continued until the disconnection message.

Bilateral teleoperation controller is implemented as shown in Fig. 7. Velocity and orientation input commands are sent through the Internet and the force inputs are made of two sources.

When the remote site operator manipulates the haptic device, velocity and orientation of the haptic device are transmitted to the SpiderBot-II using the TCP/IP protocol. At local site, both velocity and orientation are used as input command to control the SpiderBot-II motion. Desired wire length with respect to input command is computed by inverse kinematics of the SpiderBot-II. Therefore, the SpiderBot-II moves to the desired position.

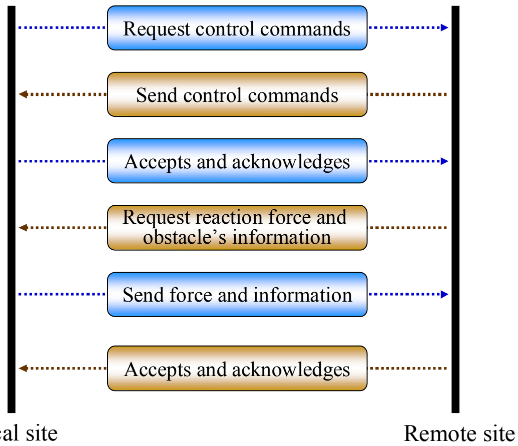


Fig. 6 Schematic representation of data communication.

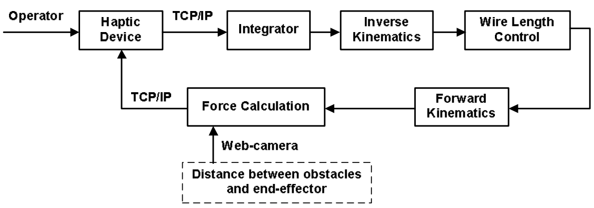
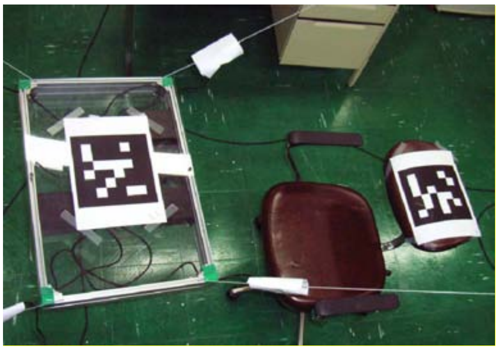


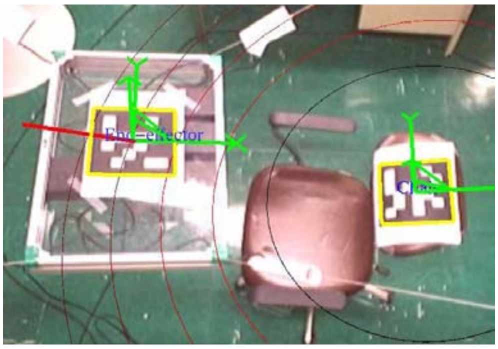
Fig. 7 Bilateral teleoperation.

5. EXPERIMENTAL RESULTS

Fig. 8 shows the implementation of the proposed system. It consists of two separate sites such as local and remote. At the local site as shown in Fig. 8(a), the software program is multi-threaded, including control loop of the SpiderBot-II, image processing loop, and communication server. And the software in the remote site is composed of three separate loops such as a process for a haptic device, image display, and communication client. We conducted experiments of teleoperation based on the marker detection and force field over the Internet. The force field which is augmented on a screen is shown in Fig. 8 (b).



(a) Local



(b) Remote

Fig. 8 Teleoperation experiments.

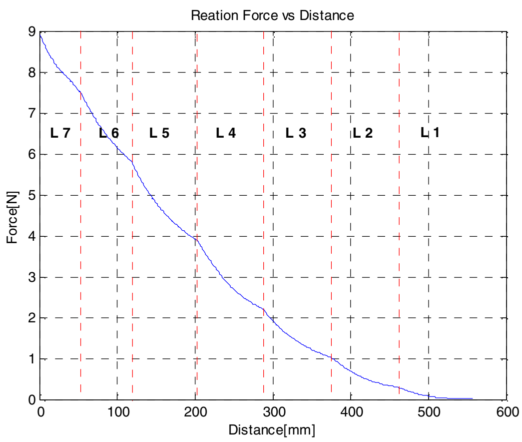


Fig. 9 Computed reaction force with respect to the distance between the obstacle and the end-effector.

Fig. 9 shows the experimental results of variation of reaction force when the distance between an obstacle and the end-effector is increase. As the end-effector is approaching an obstacle, the remote operator feels less reaction force through a haptic device. And this would be helpful for the operator to prevent the obstacle collision. Fig. 9 shows the computed reaction force when the distance is varying. As can be seen in the figure, each layer generates smooth reaction force, since reaction force computation is based on weight factors as well as distance between the end-effector and the obstacle.

6. CONCLUSION & FUTURE WORK

In this paper, we propose a teleoperation system for the wire-driven parallel robot called SpiderBot-II over the Internet using augmented reality. Augmented reality is used for the easy recognition of the obstacles in the workspace. The position and orientation of the obstacles are obtained by detection markers attached to each obstacle. Each marker has its own ID, therefore each obstacle can be identified. And by detecting the markers on obstacles and the end-effector, we can estimate the distance between them and the estimated distance can be used to generate the reaction force exerted to a remote operator. Reaction force based on the force field can help to avoid an obstacle located at local site. Furthermore, utilizing low cost web-camera and vision based tracing can be able to construct system in a cost effective way. In addition to that, display of obstacle's information such as name, dimension, and force field is helpful for manipulating the SpiderBot-II. Future work includes comprehensive user studies to show that bilateral teleoperation of the system using obstacle avoidance based on the marker detection is effective for the daily indoor activity assistance of the elderly or the handicapped. In addition, we will devise an adaptive virtual plate that is created along with dominant axis like x-y, x-z, or y-z. In this work, the single web-camera will not cover the entire working area of the SpiderBot-II due to limitation of the camera's FOV (Field Of View), so multiple cameras will be used.

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