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TELEOPERATION OF ROBOT ARMS USING FORCE-FREE CONTROL AND TEMPLATE MATCHING

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Abstract. *This paper discusses the development of a teleoperation system to control robot arms remotely combined with a vision system module. In fact, force-free control and template matching techniques are applied to control the motion of industrial robot arms via network. The system has two motion control schemes: rough motion of the robot arm is handled through teleoperation by using force-free control technique, and accurate motion is implemented by visual template matching. Switching between two control schemes is carried out from one to another appropriately to achieve the desired motion control. The effectiveness of the proposed methodology is verified by the experimental results.*

Keywords: Teleoperation, Industrial robot arm, Template matching, Force-free control (FFC), Visual servo control, Rough motion, Accurate motion

1. **Introduction.** In last two decades conventional robot arms are heavily used in industrial applications [1]. In the recent years, computer vision attached, network and teleoperation of robotics [2, 3, 4], have been paid much attention by researchers especially in emerging areas like telemedicine [5], telesurgery [6, 7], remote controlled robots in hazardous operations, undersea operations, nuclear or high radioactive rich environments [8], high temperature environments, and space or planetary explore operations [9].

This paper mainly focuses on the accurate remote control of the motion of robot arm via network. Time delays and data losses during the remote communication are two constrains to be discussed in this paper. On the other hand, the proposed control strategy is applied without any changes to the existing factory fitted controllers of robot arms. The force-free control and template matching are two separate modules and externally attached to the factory fitted components of the robot. The proposed solution has a real time control behavior, which is implemented on real-time operating system environment.

Considering the industrial robot arms in general it is difficult to move freely by applying external force (passive motion) since the servo controller behavior itself prevents the robot arm movement against the external force. In order to restrain the inherent behavior of the built-in servo controller, the technique called force-free control (FFC) was proposed by one of the authors [10]. One of the most important behavior of the FFC is that it would not involve any changes to the existing controller (factory fitted hardware or software) for the robot arm.

On the other hand, computer vision techniques with required control methodologies have been consistently studied [9, 11], and widely used among the researchers in various fields including robot vision and visual servo control systems. Template matching is known as one of applicable techniques widely used in vision control applications, and shows reasonable accuracy with the speed [12, 13], although the speed, accuracy and robustness depend on the hardware and the complexity of the algorithm expected to be used. However, template matching is currently a consistent method and proved to be a reliable derivation of visual servo applications. Therefore, this paper is based on the remote control of the robot arm by using the FFC and visual template matching schemes.

The problem of accurate teleoperation of industrial robot arms has been studied by the researchers mostly in the last two decades. However, most of the researches were based on provision of less autonomy to the remote working side (slave side) robot. And also, an important noticeable difference is that the related researches did not use or seldom used the industrial robot arms for the operational side (master side) manipulations. In most cases, virtual tool or a small joy stick type manipulator was used instead to give control commands to the slave side. Therefore, those related researches focused and directed to handle the important issues on time delays contracted in the communication channels between master and slave sides.

In [14], a method to deal with teleoperated surgery in kinematic restricted environments was proposed. However, the described system depends on the master side to make reactions to dynamic changes in the environment. The virtual force feedback approach for teleoperation without coupled visual aid was proposed in [15]. In this approach, the system is assumed to be limited to the direct communication without considering time delays and data losses during telesurgical training practices. A useful contribution to solve the problem of assuring stability of the teleoperation due to time delay was presented in [16]. A method to assist the human operator semi-autonomously by using virtual tool dynamics was also proposed in [17]. However, the accurate motion highly relies on the master side control commands.

As mentioned above, most of the researches rely on the master side control actions on teleoperation. Then, it creates traffic on the communication channels and makes definite burden to the timely information processing. In addition, most researches of the teleoperation are also highly sensitive to master side mistakes which can be expected in any human control involvement. In [18], a new enhancement for the time-delayed systems was proposed. It also can only be shown that the given results as long as the delays are finite constants and an upper bound for the round-trip delay is known. Another issue of the above approaches is that in real operations time delay adversely affected on control actions given from the master side untimely and inefficiently. To address the above problems, in our approach, autonomous image processing based visual servo control is adopted on the slave side.

In [19], the teleoperation implementation proved the applicability of the FFC through network, and the experiments were carried out to verify the technique. However, the movement of robot arm tip was restricted only to the vertical direction movement of robot arm tip, and also the vision system behavior policy was not implemented. The control scheme proposed in this paper is also applicable for the horizontal accurate motion of the tip of the robot arm. Moreover, vision system behavior policy is also illustrated, and two experiments were carried out to show the repeatability and applicability of the promising approach.

Experimental setup comprises of a SCARA-type robot manipulator for the operational side to generate reference position manually through rough motion using the FFC by a human operator, and a PUMA-type industrial articulated robot arm is used for the working side to obtain the accurate motion autonomously by means of template matching [12] upon visual servo control. The effectiveness is verified by experimental results obtained from different sets of trials.

The rest of this paper is organized as follows: In Section 2, total system is explained with details of concept and configurations of the FFC and template matching. Section 3 is devoted to the validation of the proposed system. Then, conditions of the experimental setup and outcome of the experiments are also given. Section 4 discusses the proposed system from the viewpoints of the maneuverability and network delays cum data losses. Finally, the conclusion of this paper is summarized.

2. **Teleoperation System by Force-Free Control and Template Matching.**

2.1. **Concept of the proposed teleoperation system.**

Figure 1 illustrates the schematic diagram of the proposed teleoperation control system. The system consists of two main modules as shown in the block diagram in Figure 2: (i) robot arm and (ii) two reference generation mechanisms.

Figure 1 shows the detailed implementation of rough motion and accurate motion. Upper portion gives the idea of teleoperation using FFC, where human operator manipulates the operational side robot arm in order to get the target within the view of the camera fixed on the working side robot. Lower portion illustrates the accurate motion after detecting the target object. The position commands for the accurate motion are given by the camera side computer which is connected to the working side robot locally.

Figure 2 also shows the block representation of the operational, working and camera sides in order to provide a clear view of the functions of the proposed system. It also describes how external force creates the reference position and sends the generated reference position via network channel to the working side robot. Also the camera side uses the template matching technique to detect the target position within the camera view and it generates the required reference position and sends it to the working side position controller.

The computers are interconnected through network, and TCP/IP socket communication [20] is used for both operational and working sides of the system. Rough motion is obtained manually with the aid of an external force from a human operator in the operational side by FFC, and accurate motion in working side is governed autonomously by the visual template matching method. The change of mechanisms between remote control for rough motion and visual servo control for accurate motion is handled by the vision system.

The human operator manipulates the robot arm in the operational side in order to move the robot arm in the working side. The FFC [10] is applied to the robot arm in the operational side, so that its passive motion according to the external force can be realized. The reference position of the robot arm generated by the manipulation in the operational side is sent to the working side through the network. Hence, the rough motion of the robot arm can be realized in the working side by the remote control.

The camera side of the system analyzes images obtained by the camera, and the reference position for the robot arm in the working side is calculated. Then, the reference position is sent to the working side via network. Thereafter, accurate motion of the robot arm in the working side can be realized through the visual servo control.

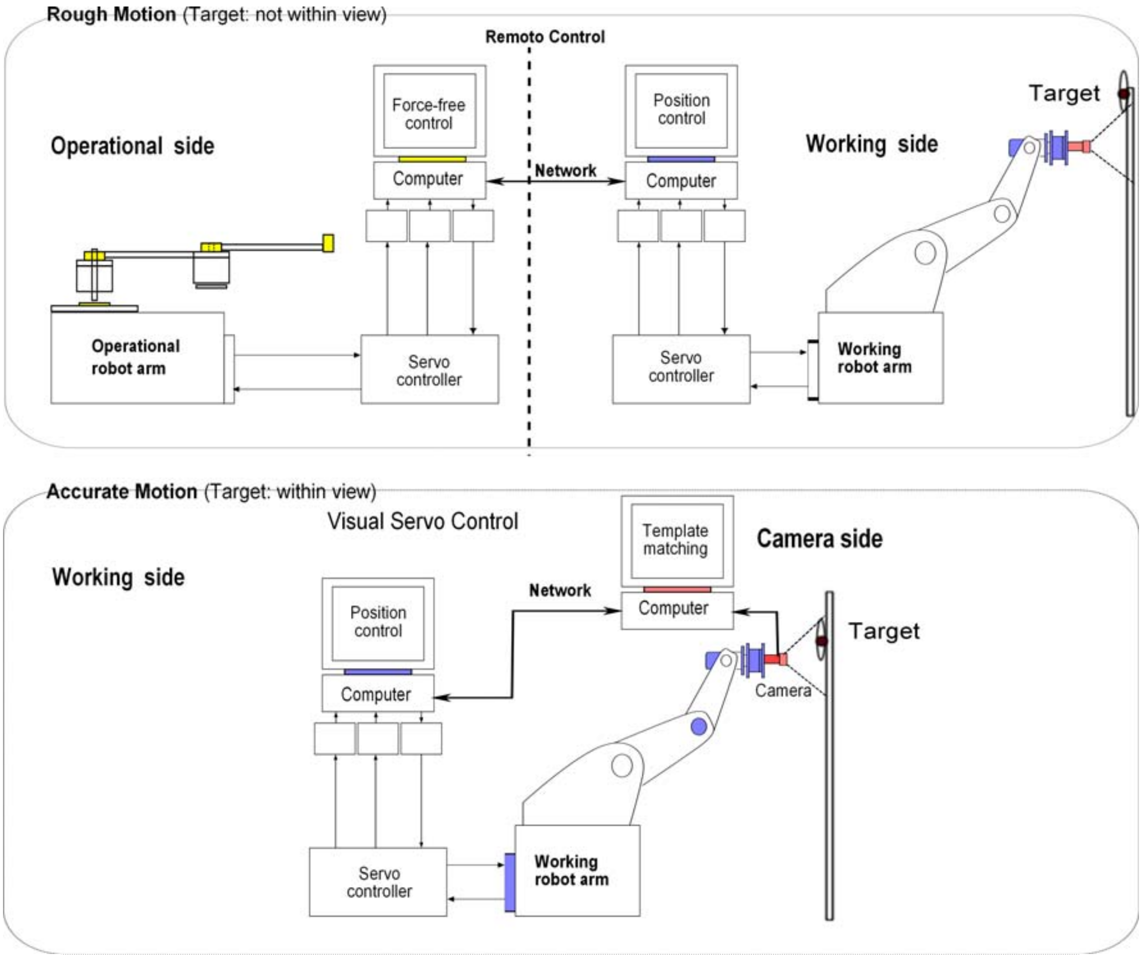


FIGURE 1. Schematic overview diagram of the proposed teleoperation system

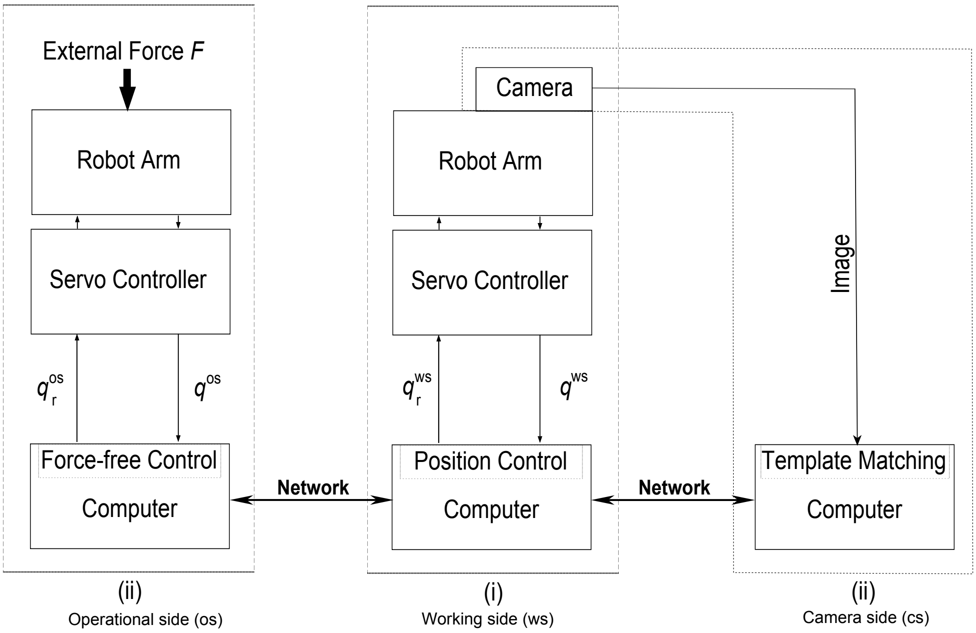


FIGURE 2. Block diagram of the proposed teleoperation mechanism

The servo controller of the robot arm in the working side is adopted as the position control. Hence, the position control realizes the following motion of the reference position of the robot arm in the working side. In the case of rough motion, the position reference is generated by the remote control module, whereas for the accurate motion, the position reference is determined by the vision system.

In the following subsections, configuration of the teleoperation setup (i.e., the remote control setup of the operational side, the visual servo control and template matching in the working side and the switching mechanism between remote control and visual servo control) is explained in detail.

2.2. **Configuration of the proposed system.** Figure 2 shows the total mechanism chart of the proposed system. The robot arm in the operational side is used to generate the reference position. The vision system in the camera side is used for detecting the target position and determining the reference position.

Figure 3 shows the total flow chart of the proposed teleoperation mechanism. The robot arm is controlled according to the reference tip position received from the reference

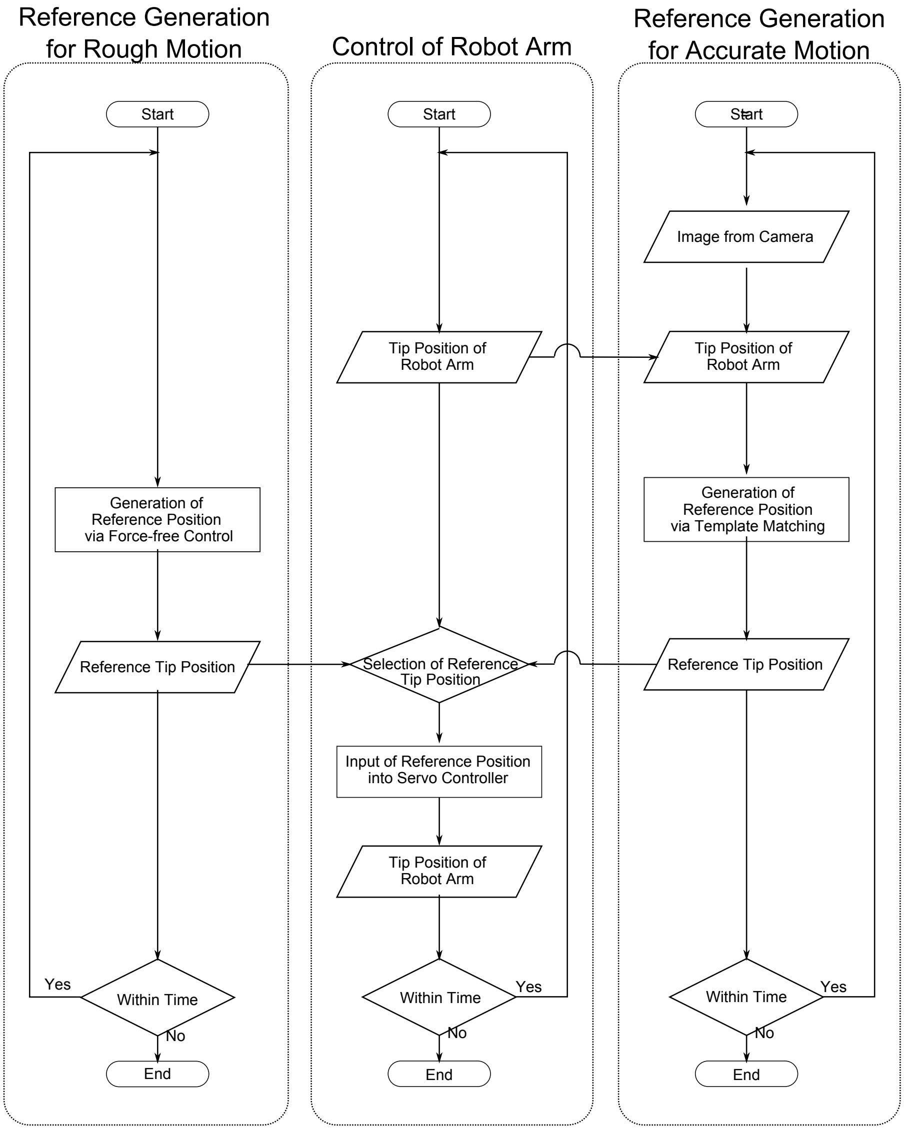


Figure 3. Overall flow chart of the proposed teleoperation system

generation mechanisms. The position control can be achieved by two kinds of motions for the reference position of the robot arm, i.e., the rough motion and the accurate motion. For the rough motion, the reference position is generated manually by using the force-free control. On the other hand, for the accurate motion, the reference position is generated automatically by using the vision system based on the template matching technique. In order to generate the reference position of the robot arm for the accurate motion, the image obtained from the Universal Serial Bus (USB) camera is analyzed and processed. The vision systems attached to the camera side is responsible for detecting the target position. The position data for the robot arm are sent through the network.

2.2.1. *Operational side (remote control behavior).* The FFC is adopted in order to realize the passive motion of the robot arm. In the FFC [10], the robot arm moves passively according to the external force as if it were under the circumstances of zero friction and zero gravity. In general, dynamics of industrial robot arm is described by

$$H(\dot{\boldsymbol{q}})\ddot{\boldsymbol{q}} + D\dot{\boldsymbol{q}} + N_\mu f_s(\dot{\boldsymbol{q}}) + \boldsymbol{h}(\dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}_{\mathbf{s}} + \boldsymbol{\tau}_F, \tag{1}$$

where $\boldsymbol{q}$ is the output vector of the joint angle, $H(\dot{\boldsymbol{q}})$ is the inertia matrix, $D\dot{\boldsymbol{q}} + N_\mu f_s(\dot{\boldsymbol{q}})$ denotes compound friction term, $\boldsymbol{h}(\dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$ is the coupling non-linear term, $\boldsymbol{g}(\boldsymbol{q})$ gives the gravity term, $\boldsymbol{\tau}_{\mathbf{s}}$ is the torque input to the robot arm and $\boldsymbol{\tau}_F$ is the torque caused by the external force [13, 21].

The ideal dynamics of the robot arm in the operational side applied the FFC is given as

$$H^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}})\ddot{\boldsymbol{q}}^{\mathrm{os}} + \boldsymbol{h}^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}}, \dot{\boldsymbol{q}}^{\mathrm{os}}) = \boldsymbol{\tau}_F^{\mathrm{os}}, \tag{2}$$

where $\boldsymbol{q}^{\mathrm{os}}$ is the position vector of joint angle, $H^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}})$ is the inertia matrix, $\boldsymbol{h}^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}}, \dot{\boldsymbol{q}}^{\mathrm{os}})$ is the coupling nonlinear term, $\boldsymbol{\tau}_F^{\mathrm{os}}$ is the joint torque generated the external force $\boldsymbol{F}$ on the tip of the robot arm in the operational side.

The dynamic of the robot arm in the operational side including the servo controller is given by

$$H^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}})\ddot{\boldsymbol{q}}^{\mathrm{os}} + \boldsymbol{h}^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}}, \dot{\boldsymbol{q}}^{\mathrm{os}}) = K_\tau^{\mathrm{os}}[K_{\mathrm{v}}^{\mathrm{os}}\{K_{\mathrm{p}}^{\mathrm{os}}(\boldsymbol{q}_{\mathrm{r}}^{\mathrm{os}} - \boldsymbol{q}^{\mathrm{os}}) - \dot{\boldsymbol{q}}^{\mathrm{os}}\}], \tag{3}$$

where $K_{\mathrm{p}}^{\mathrm{os}}$, $K_{\mathrm{v}}^{\mathrm{os}}$ and K_τ^{os} are position loop gain, velocity loop gain and torque constant of built-in servo controller of the robot arm in the operational side, respectively and $\boldsymbol{q}_{\mathrm{r}}^{\mathrm{os}}$ is the reference position of joint angle.

In order to realize the ideal dynamics (2) of the industrial robot arm, the reference $\boldsymbol{q}_{\mathrm{r}}^{\mathrm{os}}$ for the robot arm is selected as

$$\boldsymbol{q}_{\mathrm{r}}^{\mathrm{os}} = (K_{\mathrm{p}}^{\mathrm{os}})^{-1}\{(K_{\mathrm{v}}^{\mathrm{os}})^{-1}(K_\tau^{\mathrm{os}})^{-1}\boldsymbol{\tau}_F^{\mathrm{os}} + \dot{\boldsymbol{q}}^{\mathrm{os}}\} + \boldsymbol{q}^{\mathrm{os}}. \tag{4}$$

The joint torque $\boldsymbol{\tau}_F^{\mathrm{os}}$ corresponding to the external force $\boldsymbol{F}$ on the tip of robot arm is assumed to be

$$\boldsymbol{\tau}_F^{\mathrm{os}} = -(\boldsymbol{\tau}_{\mathrm{s}}^{\mathrm{os}} - \boldsymbol{\tau}_{\mathrm{d}}^{\mathrm{os}} - \boldsymbol{\tau}_{\mathrm{g}}^{\mathrm{os}}), \tag{5}$$

where $\boldsymbol{\tau}_{\mathrm{d}}^{\mathrm{os}}$ and $\boldsymbol{\tau}_{\mathrm{g}}^{\mathrm{os}}$ are described by

$$\boldsymbol{\tau}_{\mathrm{d}}^{\mathrm{os}} = D^{\mathrm{os}}\dot{\boldsymbol{q}}^{\mathrm{os}} + N_\mu^{\mathrm{os}} f_s^{\mathrm{os}}(\dot{\boldsymbol{q}}^{\mathrm{os}}), \tag{6}$$

$$\boldsymbol{\tau}_{\mathrm{g}}^{\mathrm{os}} = \boldsymbol{g}(\boldsymbol{q}^{\mathrm{os}}), \tag{7}$$

and $\boldsymbol{\tau}_{\mathrm{s}}^{\mathrm{os}}$ is the output of the torque monitor. The abbreviations "os", "ws" and "cs" mean "operational side", "working side" and "camera side" respectively.

For three modules communication protocol is TCP/IP, and therefore, the Internet technology is used as the communication platform of the teleoperation system. The Internet is commonly used as a standard platform so that our implementation is adapted easily without changing the existing hardware and/or software [19]. The socket communication via TCP/IP is applied for communication technique of the proposed system. The transmitted data from the operational side to the working side are the reference position of the robot arm in the working side, and the received data of the operational side from the working side are inputs to the servo controller for the robot arm in the working side as the reference command.

The robot arms both of the operational side and of the working side are controlled by the real time tasks at the constant sampling interval. Since the real time task behavior can not be fulfilled by the socket communication via TCP/IP, the communication must be handled by the non real time task.

The reference position generated in the operational side is transmitted to the working side via network communication. After receiving the reference position, the information is sent to the real time task of the robot arm control in the working side. Then, the robot arm in the working side is moved according to the received reference position. Therefore, even if the time intervals between the successively received reference position in the working side vary due to the undesirable effects such as communication delays, the remote control system works well.

The sequential flow of the remote control system is explained as follows:

1. The start command is transmitted from the operational side to the working side through the socket communication via TCP/IP.
2. In the operational side, the robot arm is controlled by the FFC scheme at the constant sampling time interval.
3. At the operational side, the position request is sent to the real time task. Then, the position response of the robot arm in the operational side is received.
4. Subsequently at the operational side, the reference position of the working side is calculated from the position response of the robot arm in the operational side.
5. Next reference position of the working side is transmitted from the operational side to the working side through the Socket communication via TCP/IP.
6. In the working side, the received reference position is sent to the real time task of the robot arm controller, and the robot arm is controlled at the constant sampling time interval.
7. The above process from 1. to 6. continues until the mechanism switches to the visual servo control.

2.2.2. *Working side (position control behavior).* The dynamics of the robot arm in the working side with the servo controller is expressed by

$$H^{\mathrm{ws}}(\boldsymbol{q}^{\mathrm{ws}})\ddot{\boldsymbol{q}}^{\mathrm{ws}} + \boldsymbol{h}^{\mathrm{ws}}(\boldsymbol{q}^{\mathrm{ws}}, \dot{\boldsymbol{q}}^{\mathrm{ws}}) = K_{\tau}^{\mathrm{ws}}[K_{\mathrm{v}}^{\mathrm{ws}}\{K_{\mathrm{p}}^{\mathrm{ws}}(\boldsymbol{q}_{\mathrm{r}}^{\mathrm{ws}} - \boldsymbol{q}^{\mathrm{ws}}) - \dot{\boldsymbol{q}}^{\mathrm{ws}}\}], \tag{8}$$

where $H^{\mathrm{ws}}(\boldsymbol{q}^{\mathrm{ws}})$ is the inertia matrix, $\boldsymbol{h}^{\mathrm{ws}}(\boldsymbol{q}^{\mathrm{ws}}, \dot{\boldsymbol{q}}^{\mathrm{ws}})$ is the coupling nonlinear term, $\boldsymbol{q}^{\mathrm{ws}}$ is the position of joint angle, $K_{\mathrm{p}}^{\mathrm{ws}}$, $K_{\mathrm{v}}^{\mathrm{ws}}$ and K_{τ}^{ws} are position loop gain, velocity loop gain and torque constant for the robot arm in the working side, respectively.

The tip position $\boldsymbol{p}^{\mathrm{os}}$ of the robot arm in the operational side is calculated from the joint position output $\boldsymbol{q}^{\mathrm{os}}$ as

$$\boldsymbol{p}^{\mathrm{os}} = f^{\mathrm{os}}(\boldsymbol{q}^{\mathrm{os}}), \tag{9}$$

where f^{os} means the forward kinematics of the robot arm in the operational side.

2.2.3. *Camera side (visual servo control by template matching).* The template matching is applied to images obtained from the USB camera at each sampling time. The template matching is carried out by using the image for the target object obtained in advance. Both images for the target object and the image obtained from the camera are converted

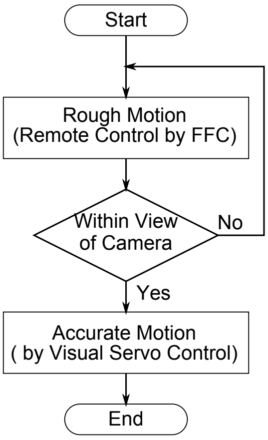


Figure 4. Concept flow chart of switching of remote control to visual servo control

into gray-scale versions. The gray-scale image for the target object is resized according to the distance between the camera and the target object. Then, the target position in the image is obtained by the template matching, where the direction is conducted by using an appropriate criterion such as the sum of squared differences of the brightness between two images [12]. The reference position vector from the camera side (cs), $\boldsymbol{p}^{\mathrm{cs}}$ is determined in such a way that the center position of the target is coincided with that of the image obtained from the camera by using the distance calculation between the two center positions.

The target position is determined as follows:

1. Images are taken from the USB camera at each sampling time.
2. To process the image, acquired image is converted from *jpeg* format to *RGB* format.
3. Template matching method is used to determine the target position.
4. The detected target position is sent to the operational side through socket communication by using TCP/IP.

2.2.4. *Switch from remote control to visual servo control.* Figure 4 shows the flow diagram of the switching mechanism from remote control to visual servo control. The rough motion is handled by the remote control upon FFC scheme. If the USB camera detects the target followed by sequential template matching [12], the working side robot arm moves to the target position by using the visual servo control. In this approach, reference position $\boldsymbol{p}^{\mathrm{cs}}$ is selected if there is the target object in the image detected and obtained from the camera. If not, the reference position $\boldsymbol{p}^{\mathrm{os}}$ is selected,

$$\boldsymbol{q}_{\mathrm{r}}^{\mathrm{ws}} = \begin{cases} (f^{\mathrm{ws}})^{-1}(\boldsymbol{p}^{\mathrm{os}}) & (\text{if } \boldsymbol{p}^{\mathrm{os}} \text{ is selected}) \\ (f^{\mathrm{ws}})^{-1}(\boldsymbol{p}^{\mathrm{cs}}), & (\text{if } \boldsymbol{p}^{\mathrm{cs}} \text{ is selected}) \end{cases} \tag{10}$$

where f^{ws} and $\boldsymbol{q}_{\mathrm{r}}^{\mathrm{ws}}$ stand for the kinematics of the robot arm to be controlled and reference of joint angles, respectively. Target detection from the camera image is carried out by using the method of setting threshold criterion in term of the brightness values [12, 13]. In our experiments, constant light conditions are assumed.

3. Validation of the Proposed Teleoperation System.

3.1. **Experimental condition.** The effectiveness of the proposed teleoperation system is assured by experiments. The experimental study was carried out using actual robot

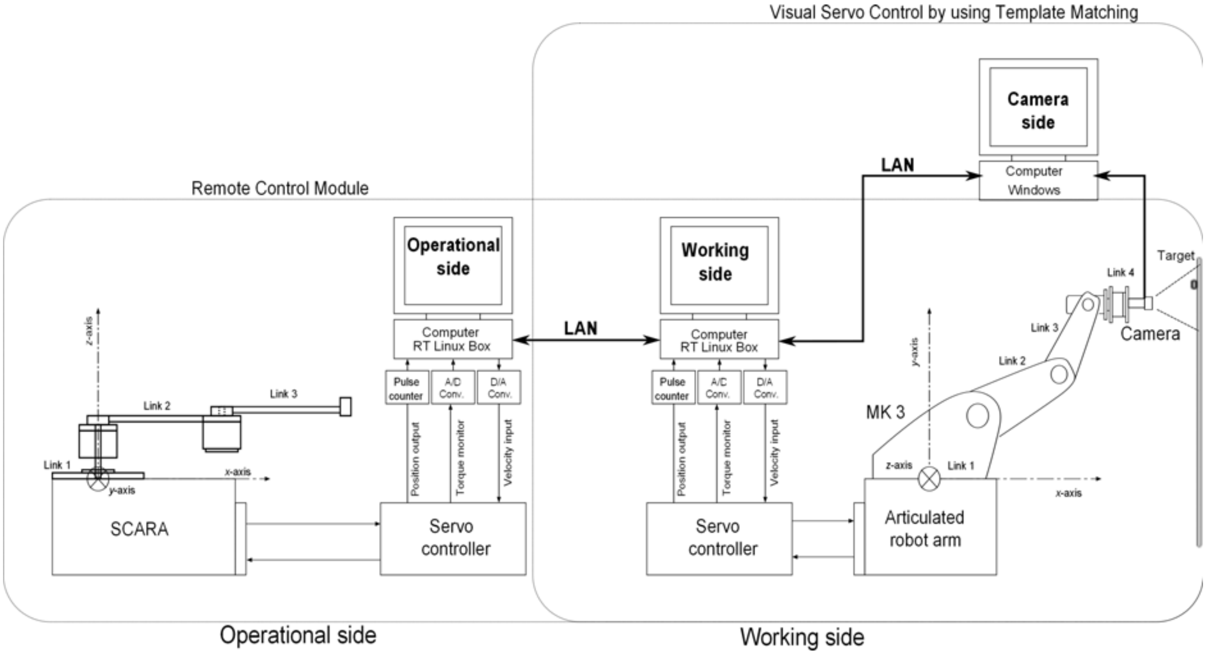


Figure 5. Experimental setup diagram of the proposed teleoperation system

arms connected with LAN. Figure 5 shows the diagram of experimental setup for the proposed teleoperation system.

A vertical articulated robot arm, Performer MK3s *(Yahata Electric Machinery Mfg. Co. Ltd.)* was used for the robot arm in the working side, and a SCARA was used for the robot arm in the operational side. The parameters of these robots are shown in Table 1. The position loop gain was given as $K_{\mathrm{p}}^{\mathrm{ws}} = 25I$ [1/s] and the velocity loop gain was given as $K_{\mathrm{v}}^{\mathrm{ws}} = 150I$ [1/s] for Performer MK3s, and the position loop gain was given as $K_{\mathrm{p}}^{\mathrm{os}} = 2I$ [1/s] and the velocity loop gain was given as $K_{\mathrm{v}}^{\mathrm{os}} = 120I$ [1/s] for SCARA. The real time behavior for both position and force-free control was established by the RT-Linux environment. The sampling interval of the real-time task for the robot arm control was 4 [ms], the time interval of the reference position generation in the non-real time task of the operational side was approximately 50 [ms], and the time interval of visual servo control was approximately 200 [ms]. For SCARA, Link 2 and Link 3 were used. For Performer MK3s, Link 1, Link 2, Link 3 and Link 4 were used. This means that we can achieve the accurate motion for not only y-direction but also z-direction. Then, Link 4 is controlled so as to maintain the direction of the camera horizontally.

Table 1. Parameters of performer MK3s and SCARA robot

	MK3s	SCARA
Resolution	8192	8000
Gear ratio of Link 1	120	–
Gear ratio of Link 2	160	50
Gear ratio of Link 3	160	50
Gear ratio of Link 4	100	–
Length of Link 1 [m]	0.36	–
Length of Link 2 [m]	0.25	0.3
Length of Link 3 [m]	0.215	0.315

The following assumptions and conditions are made for the proposed system and for all the experiments.

1. The changes of external environment factors such as illumination level of the working area are assumed to be negligible.
2. Skills and cognitive factors of the human operator are remained unchanged throughout the experiments.
3. Locations of the master and slave robots are fixed and also network traffic on communication channels, therefore, time delays and data loses are assumed to be constant for given experimental results.
4. The template matching technique used in the experiments is sum of square difference (SSD). We assume SSD accuracy to remain unchanged during all the experiments.
5. The SSD is known as light weight algorithm, so that computational burden issues are homogeneous and assumed to be minimal throughout the experiments.

The USB camera used (we used a general purpose web-cam for this experiment) during the experiments is MiniCam2 *(V-Gear, Asiamajor Inc.)*. The proposed system claims to be able to work with any type of USB camera which merely depends on the degree of accuracy needed. Therefore, the robot manipulator at the working side will be able to operate with any type of plug and play camera after applying a few changes on settings if necessary. However, our experimental setup for these experiments was confined to the local area network on TCP/IP. Since our teleoperation system carries out the control of the robot arm through the Internet, the working side can be located in either a distant location of the local country or different geographical location anywhere in the world.

Before experiments, we need to give the threshold value for the template matching algorithm. The sum of squared differences was adopted as the index to evaluate the brightness of images. The pre-requisite experiment was carried out to find the average value for the threshold upon the same environmental conditions and same target button. In the experiment, we took the readings as follows:

1. Size of the template image was configured as 74 × 72 [pixels] and camera image size was configured as 288 × 352 [pixels].
2. Read the SSD value when the USB camera detects the target button, was approximately 7000.
3. Again read the SSD value when the USB camera is away from the view of the target button, was approximately 22000.
4. The average 14500 of both readings for template matching algorithm was selected as the threshold.

The robot arm in the operational side is moved passively according to the external force applied by a human hand. Therefore, robot arm, Performer MK3s will have to be controlled as to bring the tip of the robot arm to reach the target position.

3.2. **Experimental results by actual industrial robot arms.** The experimental outcome was obtained from a series of experiments. The experiments were carried out using actual robot arms. For the illustration, two of them are described in this paper. The effectiveness of the proposed teleoperation system is assured by comparison of them. The outcome from the two different trials are illustrated in Figures 6-9. The actual robot arms were connected via LAN including the mounted USB camera on the working side Performer-MK3s robot. Figures 6 and 7 are given by the reference positions for rough motion and accurate motion, respectively. Figure 8 shows the time evolution of the robot arm tip position and the corresponding reference position of the working side robot arm tip.

Table 2. Communication data format for operational side (os) to working side (ws)

Transmit data	Time[s]	Position reference x^{os}[m]	Position reference y^{os}[m]
Received data	Time[s]	Position output $x_{\mathrm{r}}^{\mathrm{ws}}$[m]	Position output $y_{\mathrm{r}}^{\mathrm{ws}}$[m]

Table 3. Communication data format for camera side (cs) to working side (ws)

Transmit data	Time[s]	Position reference y^{cs}[m]	Position reference z^{cs}[m]
Received data	Time[s]	Position output $y_{\mathrm{r}}^{\mathrm{ws}}$[m]	Position output $z_{\mathrm{r}}^{\mathrm{ws}}$[m]

Figure 9 shows sequential plots of the locus of the tip position and symbol '×' indicates the switching point from rough motion to the accurate motion for each experiments.

Notations for the experiment result graphs are as follows. Tables 2 and 3 denote data format and the notations of the experiments. In Figure 6, $\boldsymbol{p}^{\mathrm{os}} = (x^{\mathrm{os}}, y^{\mathrm{os}})$ is the reference position sent from the operational side (os) for x-direction and y-direction, and in Figure 7, $\boldsymbol{p}^{\mathrm{cs}} = (y^{\mathrm{cs}}, z^{\mathrm{cs}})$ is the reference position sent from the camera side (cs) for y-direction and z-direction.

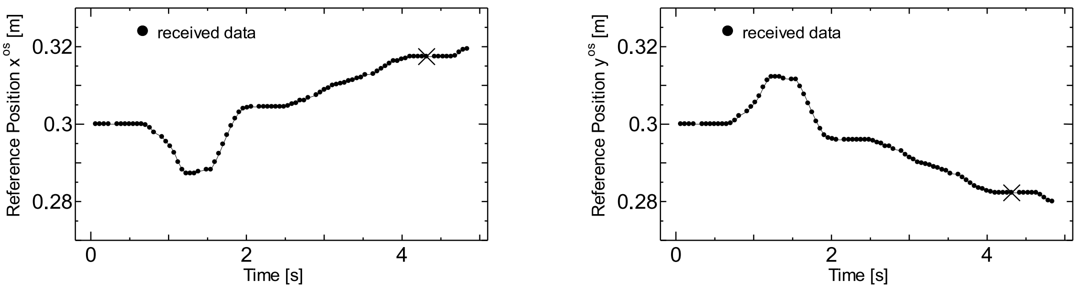
The tip positions of the robot arm in the working side behaved according to the reference position in the operational side until 4.32 [s] for the experiment (1) and 3.30 [s] for experiment (2), respectively. Then, the control strategy was changed from the remote control to the visual servo control. The tip position was closed to the camera side reference position. Finally, the tip position of the robot arm in the working side reached the target position, where target was created by using a round black button of 0.02 [m] diameter, fixed on the board as shown in Figure 4. Target was fixed for both experiments, and located at 0.51 [m] away from the x axis, 0.64 [m] high from the y axis and 0.05 [m] from z axis of the robot base in the working side. The results show that the teleoperation system combined with the remote control and the visual servo control can be successfully operated.

4. Discussion.

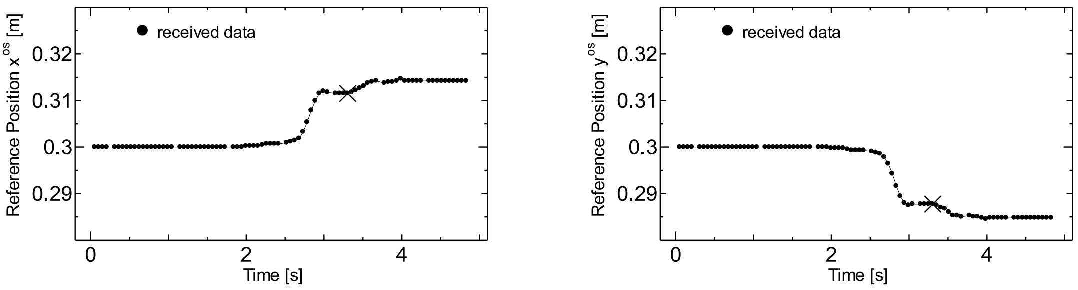
4.1. Maneuverability.

Although, in the proposed system, human operator is required to operate the robot arm in the working side by means of force-free control, it handles only the rough motion through the remote control. Then, after receiving the reference position from the operational side, the accurate motion of the robot arm in the working side can be initiated autonomously by using the template matching cum visual servo control. Besides, the behavior of our proposed system has two motion steps to reach the desired target of working side robot arm to move. Therefore, requirement of the human operator is to move the robot arm in the operational side whose operation will be reflected in the working side (where the target is located) within the frame of the USB camera mounted on the robot arm in the working side. Thus, the handleability of the proposed teleoperation system is high enough to execute more complex movements as per the operator's expectations.

The most important aspect is that, we can use servo controller of the industrial robot arm, without changing the factory fitted configurations. Therefore, any robot arm can be used for this application theoretically. The additional software of the force-free control and communication program is enough for the realization of the teleoperation system. In addition, a common type of USB camera with a computer to process the images can be attached to the robot arm separately in the working side to acquire the accurate target position control. The advantage of the above brings flexible teleoperation system

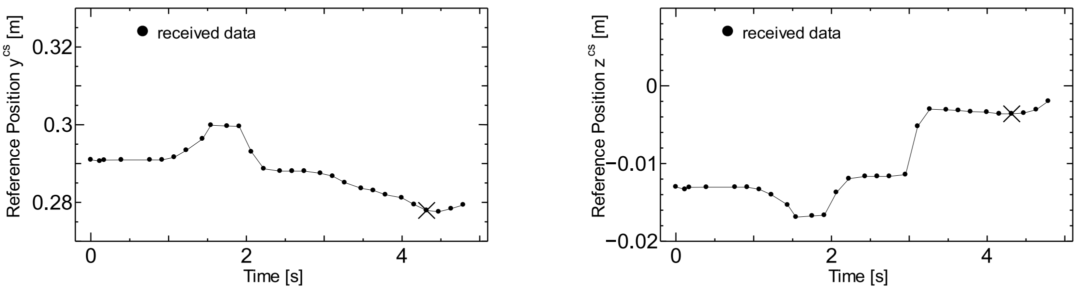


(a) Experiment 1

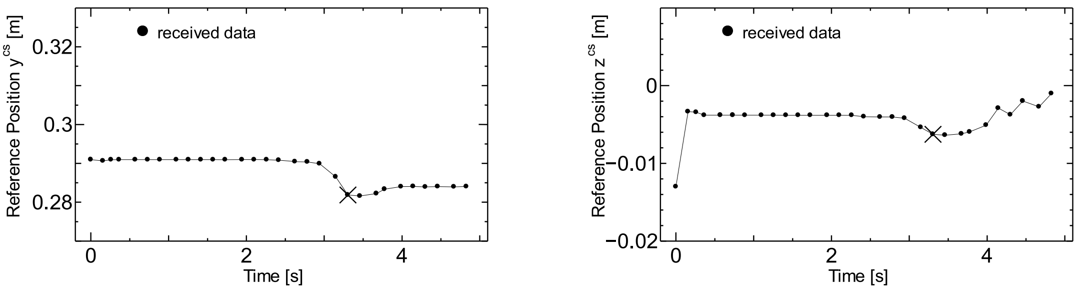


(b) Experiment 2

FIGURE 6. Reference position generation with time by force-free control for experiment number 1 (top) and 2 (bottom)

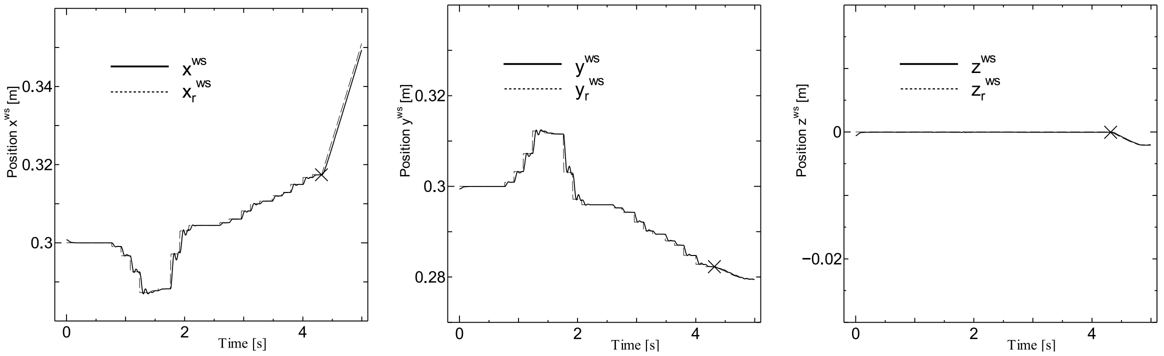


(a) Experiment 1

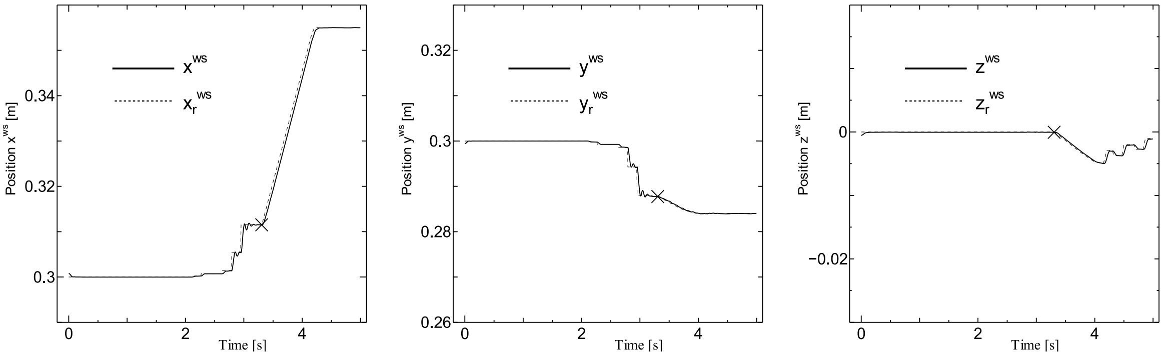


(b) Experiment 2

FIGURE 7. Reference position generation with time by template matching for experiment number 1 (top) and 2 (bottom)



(a) Experiment 1



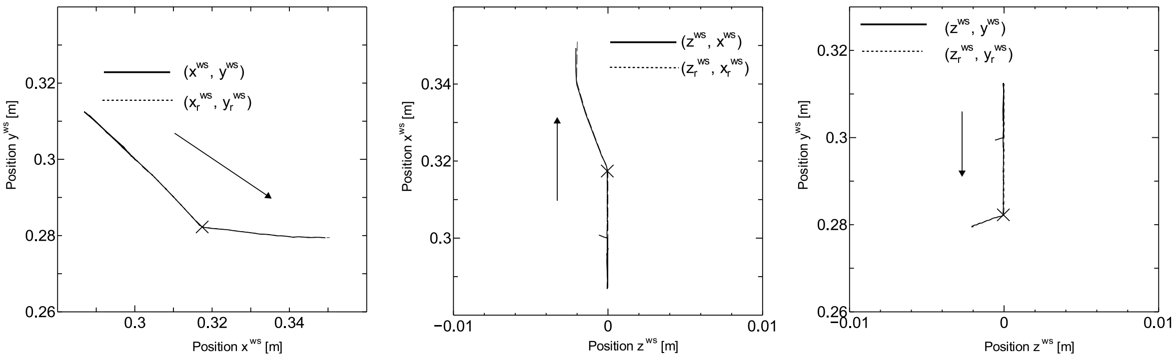
(b) Experiment 2

FIGURE 8. Tip position of the robot arm in the working side

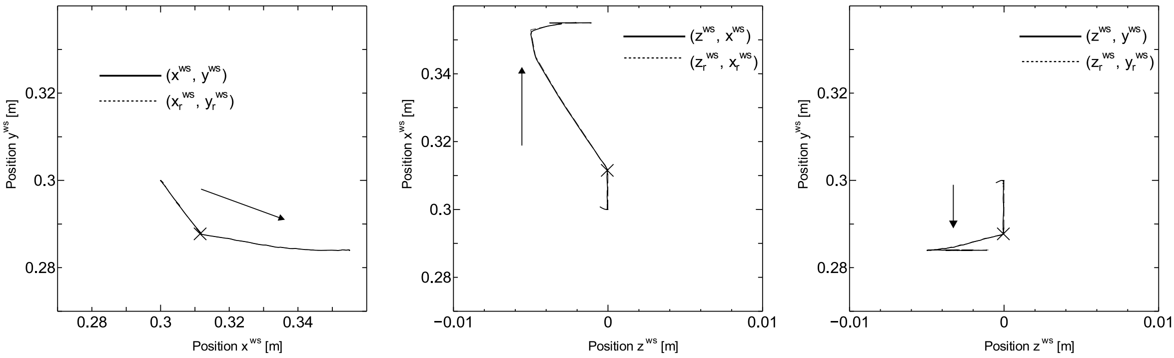
configuration by use of the appropriate mechanism selection of FFC followed by visual servo control for the operational side and for the working side.

4.2. **Accountability of network delays and data losses.** Our aim is to make a teleoperation robot control system that will work between two geographical locations in any part of the world. Therefore, the Internet technology is identified as a readily available and suitable communication platform to be used for the proposed system. The socket communication via TCP/IP may include communication delay and data losses which may also create inconsistency when transferring data. With respect to the communication delay, the influence may appear as a delay of the robot arm motion in the working side from the motion in the operational side because the reference position generated in the operational side is transmitted to the working side, and the robot arm in the working side is moved according to the received reference position with communication delay. Due to the lack of required data of corresponding reference positions, the consequence of data losses may be reflected as an awkward or an undesirable robot arm movements in the working side. By considering the remote control behavior, communication delay obviously defects the maneuverability of the teleoperation system. Although, in this research, communication delay may also be incurred to our teleoperation system, communication delay is caused to the rough motion behavior of the robot arm in the working side. Hence, the communication delay is not going to be a critical factor to be handled for the proposed system as accurate motion is totally carried out by the working side visual servo control under real time conditions.

4.3. **Practical usability and advantages.** The proposed system was tested using actual industrial type robot arms in both master and slave sides. The results show the



(a) Experiment 1



(b) Experiment 2

FIGURE 9. Locus of the tip position of the working side

accurate motion of the working robot that brings the tip of the robot arm to the desired target position. Our motivation is to implement teleoperation system without changing existing servo controllers of the industrial robots used in both master and slave sides. The proposed teleoperation system was achieved by introducing external control software modules for FFC and visual servo control and a low cost USB camera. In our specific approach, the idea of using an industrial type robot arm in the operational side stems from the fact that, in the present time, industrial robot arms are commonly available in most of the countries. We found that it is highly versatile if one can varify an accurate teleoperation by using existing robots without major changes to their controllers. In practice, the proposed teleoperation system can be verified with an addition of extra software modules along with a few required configuration changes and an available low cost Internet communication channel. The above capability proves that in any situation like hazardous or an emergency, the proposed system can be applied even if the working robot is located in a remote location. By adopting the Internet technology, it can accurately be controlled remotely by using an industrial type robot arm located anywhere by means of minor configuration changes and human operator assistance. Moreover, it is important to state that the operation side industrial robot arm need not to be so accurate or precise in operation so that a low cost or an old robot arm can be used in the operational side as it is used only to provide rough motion reference position for the slave robot. Therefore, we also contribute to propose a low cost teleoperation system by means of integrating FFC and visual servo control techniques, where the proposed system can be configured for the existing industrial robots when teleoperation needs to be performed.

The proposed system provides an accurate motion control autonomously in the working side robot. Therefore, the system would compensate burdens due to the master control time delays and human operator mistakes to greater extent. The above facts give evidence to the fact that proposed teleoperation system has been a significant alternative solution to handle the existing problems of time delays, data losses and irregular communications of the current context of teleoperation. To accomplish the solution, the system needs a few command data from the master side as supervisory control. The high degree of slave side autonomy feature for accurate control scheme brings the system tradeoff by reducing processing complexities and computational and communication burdens.

5. **Conclusion.** In this research work, teleoperation of robot arm by means of force-free control and visual template matching was proposed. The reference position of the working side robot arm was generated by two control schemes, called rough motion and accurate motion. Two control schemes were executed; the remote control was achieved by means of force-free control, and visual servo control scheme was developed using template matching. The effectiveness of the proposed approach was verified by the experiments. Indeed, two sets of experimental results were provided to assure the repeatability of the proposed system. At this stage, since each of the experiments were conducted without changing light, glare, illumination conditions, these result are not assured and guaranteed to be used under different environment conditions.

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