

Design of an Intermediate Layer to Enhance Operator Awareness and Safety in Telesurgical Systems

Jang Ho Cho, Pål Johan From, Magnus Annerstedt, Anders Robertsson, and Rolf Johansson

Abstract—This paper presents a novel control architecture for enhanced operator awareness and improved safety in telesurgical systems. We introduce an intermediate layer between the master and slave sides which allows us to modify the slave motion for safety and the force feedback for operator awareness. The intermediate layer is then designed with a performance objective for the specific task at hand. The control scheme is validated via experiments using a suture and an industrial manipulator. More specifically we show that operator awareness should be implemented as an integrated part of the safety level to maintain safety during surgery.

I. INTRODUCTION

Minimally invasive telesurgical systems provide an ergonomic, efficient, and safe environment for surgeons to perform both in-house and long distance teleopertaion tasks [1]. Robot-assisted telesurgical systems also allow for more dexterous surgical procedures than classic laparoscopic surgery in addition to enhanced overall performance, for example by scaling and filtering out hand tremor [2]. One criticism of these systems is the steep learning curve for surgeons [3]: novice surgeons are commonly suffering from suture breakages or knot failures due to the absence of haptic feedback in commercialized telesurgical systems.

Because the surgeon is controlling the remotely located robot based on her/his visual and haptic perceptions, the information transmitted to the surgeon has to be properly designed so that both the human operator's characteristics and safety issues are taken into account. In other words, the control objectives of telesurgical systems have to be designed with the characteristics of the specific problem in mind. An interesting point in this setting is that the direct haptic feedback (or transparency-optimized haptic feedback) is not the best way to detect for example the suture breakage force [4], [5]. Along with the previous research, we focused on the enhancement of the human operator's sensitivity to detect a specific force [6]. In this paper, we propose a unified framework to enhance operator awareness and improve safety in tasks where direct haptic feedback and transparency alone cannot ensure the required safety of the overall system.

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J. H. Cho, A. Robertsson, and R. Johansson are with the Department of Automatic Control, Lund University, PO Box 118, SE-221 00 Lund, Sweden. jangho@control.lth.se

P. J. From is with the Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences, Postbox 5003, 1432 Ås, Norway and partly with the Department of Automatic Control, Lund University.

M. Annerstedt is with the Department of Urology, Herlev University Hospital, Herlev Ringvej 75, 2730 Herlev, Copenhagen, Denmark.

To this end, we propose an intermediate layer which allows us to design desired position and force references of master and slave that can take different performance objectives into account. The controllers in the intermediate layer focus on the enhancement of the operator awareness and improved safety according to potential problems in telesurgery, such as suture breakages and collisions between the surgical tool and the environment.

The concept of the intermediate layer presented in this paper has many similarities to conventional approaches and can for example be compared to haptic feedback based on position constraints. God-object methods [7], [8] and a proxy-based method [9] have been proposed to provide a haptic feedback interacting with virtual objects. The interaction between the robot and real environments [10], [11] as well as the obstacle avoidance [12], [13] can also be compared with the framework presented. The intermediate layer presented in this paper, however, allows for more general structures for enhanced operator awareness than the approaches mentioned above.

The remainder of the paper is organized as follows: The concepts of operator awareness and operator non-awareness in telerobotics is discussed in Section II together with a short discussion on safety and active interventions from the control system. The intermediate layer, which is the main topic of the paper, is introduced in Section III. The experimental results with an industrial robot and a suture are presented in Section IV. A summary and some remarks conclude the paper in Section VI.

II. OPERATOR AWARENESS AND SAFETY

Collisions between the surgical robot and human organs which are not intentionally targeted by the surgeon should always be avoided. This is in many cases challenging because the operating area is often located very close to the organs that need to be protected from direct contact with the robot. In case of prostate cancer surgery, for example, the operational space is very small and it is therefore difficult for the surgeon to avoid undesirable collisions between the robot arm and pelvis bone. This motivates the need of improved safety and enhanced awareness during these surgical procedures.

To avoid unwanted situations such as collisions or suture breakages, it is often not sufficient with a direct haptic feedback in addition to the visual feedback in the conventional way. To increase safety during surgery, we propose to implement an intermediate layer shown in Fig. 1 which is described in more detail in the next section. The intermediate

layer allows us to increase performance in two important ways—by a safety level that modifies the slave position x_s into a new variable \hat{x}_s with the objective of improving the overall safety of the system; and an awareness level that modifies the feedback force F_m into a new feedback force \hat{F}_m which represents enhanced operator awareness.

The safety level is to be interpreted as an active intervention from the control system, i.e., the control system overrides the operator and changes the slave reference \hat{x}_s . This can be done to avoid collisions, prevent suture breakage, or to increase the overall performance of the surgery in some way, for example by applying the optimal force during suturing. This active intervention can be executed in one of two ways—with or without operator awareness.

1) Operator Non-awareness: During teleoperation it is important to allow the operator to concentrate on the actual task that the operator is to perform and minimize all disturbing impressions and distractions that might take focus away from the principal task. In some cases it is therefore desirable for the control system to take actions without the operator being aware of the action. One example is collision avoidance of the robotic arm: the operator should concentrate on the end-effector motion and forces, and an action that is taken in order to avoid collisions between the robot arm and its environment should therefore not necessarily be communicated to the operator if it does not affect the operation itself. Also, redundant arms may be controlled to avoid collisions and to improve dexterity by reconfiguration of the manipulator arm—both these tasks should in general be performed without taking the operator's attention away from the main task. These actions therefore belong to the operator non-awareness layer. This layer modifies the slave position but not the master force \hat{F}_m or the visual feedback. It is typically taken from the null space of the robot so that the end-effector motion x_s is normally not affected by the action.

2) Operator Awareness: On the other hand, if the controller overrides the operator in such a way that the response of the slave takes on an unnatural behavior or impedes the operation in some way, it is important that this is communicated back to the operator in such a way that she/he understands why this safety action is taken. For example, if the end effector of the master arm is pushed away from an obstacle, this should be communicated to the operator through haptic or visual feedback. Thus, the operator awareness layer typically modifies both the slave motion \hat{x}_s and the master force \hat{F}_m .

Finally it is of course possible to modify the feedback force and not the slave position. In this case the operator is only notified through the awareness level and the safety of the system relies on the response of the operator to this feedback. The safety of the operation is ensured by increasing the awareness of the operator but no action is taken to override the operator in any way. This is useful in both collision avoidance and in suturing tasks, which we will study in more detail below.

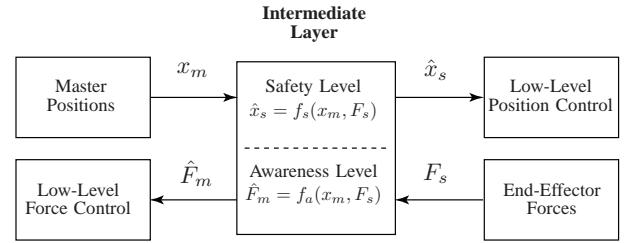


Fig. 1. The intermediate layer architecture with a safety level producing a safe position reference \hat{x}_s and an awareness level producing a feedback \hat{F}_m to the operator.

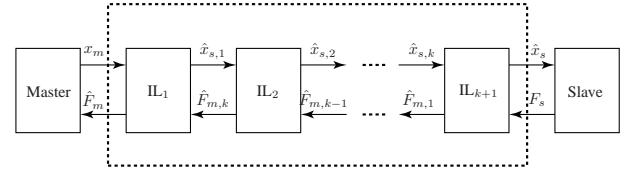


Fig. 2. The intermediate layer represented by several sub-layers in a serial connection.

III. INTERMEDIATE LAYER

From the discussion in the previous sections we see that in order to prevent potential hazards, direct haptic feedback to the operator in the conventional way is often not sufficient. More flexibility is thus needed to maintain the high safety requirements in for example surgical robotics. We propose an intermediate layer in which these safety and awareness measures can be implemented as one solution to this problem. In this section we propose the intermediate layer as one intuitive solution to implement the safety and awareness levels discussed in the previous section. The framework is, however, general and other layers that modify the position and force references can be added as desired. This includes, among other levels, algorithms for intelligence, robotic skill learning, and cognition.

A. Two-port Network Representation

Teleoperation systems can be modeled as two-port network systems [14]. According to the concept of two-port networks, each component of the teleoperation system is modeled as an individual two-port model. Then, the intermediate layer is introduced between the master and the slave two-port models. Furthermore, the intermediate layer can also contain several sub-layers. Therefore, if there are several Intermediate Layers IL_i , they can be serially connected with the input/output characteristics of each sub-system. The overall bilateral system, including the intermediate layer with possible sub-layers, is depicted in Fig. 2.

The sub-levels of the intermediate level can be serially connected to obtain the required overall performance of the system. Each sub-level can then be designed to represent one specific performance objective. Some simple examples are described in the following:

1) Awareness Layer: One way to improve the performance of the overall system is to enhance the operator awareness to certain characteristics in the operational space.

This enhanced awareness is typically obtained by creating an artificial feedback to the operator through the haptic device. Visual feedback is also frequently used to enhance operator awareness.

2) *Safety Layer*: The safety layer differs from the awareness layer in that it actively overrides the operator commands by employing a safer path than the one given as a reference by the master device. Safety can be obtained by implementing a stand-alone safety layer—which makes this an operator non-awareness layer—or in combination with an awareness layer as described above—which results in an operator awareness layer.

3) *Intelligence and Cognition*: Artificial intelligence and learning algorithms can also be implemented as a sub-layer. For certain teleoperation tasks we might want the robot to perform some part of the operation in an autonomous or semi-autonomous way. In this case this autonomy can be implemented as a sub-layer, possibly in combination with the other layers described above.

Passivity-based controllers are commonly used to control bilateral teleoperation systems with two-port network representations [15], [16]. To ensure the stability of the overall system when the intermediate layer is introduced, a class of controllers based on the passivity concept can be easily employed. Since the input/output pairs of the intermediate layers are introduced with position/force (which are different from the original PO/PC method – velocity/force), we will explain how to apply PO/PC in this case. Let us assume that the master device takes the position as an input and provides the force as an output as shown in Fig. 1. Since the overall system is computer-controlled system, x_m is sampled and \hat{F}_m is delivered low-level force controller with zero-order hold (ZOH). Then the generated energy during one-sample period, $[t_{k-1} \leq t \leq t_k]$, can be written as follows.

$$\int_{t_{k-1}}^{t_k} \hat{F}_m(t_{k-1}) \dot{x}_m(\tau) d\tau = \hat{F}_m(t_{k-1})(x_m(t_k) - x_m(t_{k-1})).$$

By summing up overall samples, the total generated energy can be represented as

$$\int_0^{t_k} \hat{F}_m(\tau) \dot{x}_m(\tau) d\tau = \sum_{j=0}^k \hat{F}_m(t_{j-1})(x_m(t_j) - x_m(t_{j-1})).$$

The same idea also can be applied to the slave side so that PO can be implemented with position-force ports. Then, we can construct PC at each sides with same algorithms as proposed in [17]. This is a straight-forward extension of PO/PC for teleoperation systems [17] with sampled PO/PC idea [18].

B. Designing Intermediate Layers

Since the position tracking is one of the most frequently used tasks in telesurgical systems, the intermediate layers in this section are developed at the position level, but easily generalized to other input-output pairs. By employing local position controllers at joint level, position-constraint-based intermediate layers can easily be adapted with forward and inverse kinematics. In this paper we will consider the design

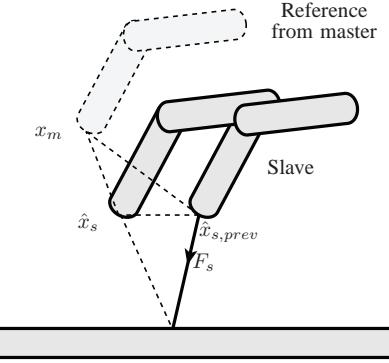


Fig. 3. The schematic diagram of *IL-LIM*. If F_s is greater than F_{lim} , the position reference to the slave robot, \hat{x}_s , is modified according to the safety level. The operator perceives the feedback force modified by awareness level.

of two types of layers: *IL-LIM*, limiting the interaction force at a specific level; and *IL-COL*, preventing unwanted collisions. However, as already stated, the intermediate layers can be modified or designed according to the specific objectives of the task and the awareness level to be designed.

1) *Limiting Interaction Forces*: Based on the ideas above, the algorithm *IL-LIM* is developed. Excessive interaction forces with the environment can be prevented by using the measured forces of the robot end effector. The problem is defined as an n degrees-of-freedom case so that $x_m, \hat{x}_s, \hat{x}_{s,prev}, F_s, \hat{F}_m \in \mathbb{R}^n$. $\hat{x}_{s,prev}$ represents the previous sample of \hat{x}_s . $F_{lim}, k_{lim} \in \mathbb{R}$ are design parameters and stand for the force to be limited and the stiffness to be designed for operator awareness.

To prevent that \hat{x}_s increases in the direction of F_s , two conditions need to be checked, these are

- $F_s > F_{lim}$; and
- $x_{dist} \cdot F_s < 0$,

where $x_{dist} = x_m - \hat{x}_{s,prev}$. The second condition checks whether the motion of the master is opposite to the direction of the force or not. The schematic diagram of updating \hat{x}_s is drawn in Fig. 3.

The problem with this approach is when slave motion \hat{x}_s is constrained and not allowed to move. In this case, if *IL-LIM* transfers F_s directly to the master, the operator will in many cases not perceive the real environment impedance. For enhanced operator awareness, we therefore add an artificial force proportional to $x_m - \hat{x}_{s,prev}$. The algorithm for *IL-LIM* is found in the Appendix. The problem of limiting the interaction forces is discussed in more detail in Section IV.

2) *Collision Avoidance*: In case of collision avoidance, we assume that objects in the environment are modeled as surfaces $\mathcal{S}(x)$. To know the minimum distance between $\mathcal{S}(x)$ and $\hat{x}_{s,prev}$ and to the closest point on $\mathcal{S}(x)$, a distance function is employed and find the closest point x_{prx} . Similar with *IL-LIM*, the direction of the motion x_m and the gradient of the surface $\mathcal{S}(\hat{x}_{s,prx})$ are compared. The schematic diagram of *IL-COL* is shown in Fig. 4. The main idea of *IL-COL* is a straightforward extension of *IL-LIM* and the algorithm of *IL-COL* can be found in the Appendix.

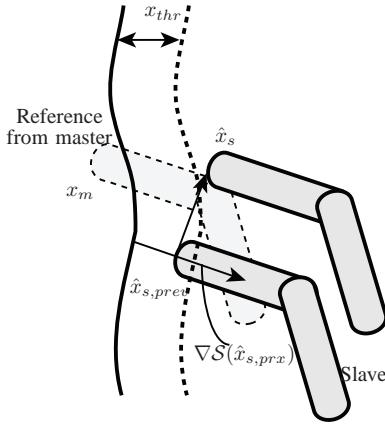


Fig. 4. The schematic diagram of *IL-COL*. If the distance between x_m and the surface $\mathcal{S}(x)$ is smaller than x_{thr} , both \hat{x}_s and \hat{F}_m are modified by the intermediate layer.

IV. A CASE STUDY: SUTURES

In this section, we study the suturing task in medical applications. Suturing is one of the most frequently performed tasks and also very challenging. One common difficulty, especially for novice surgeons, is to control the force that the robot applies to the suture. We select a suture¹ widely used in robotic surgery. It sustains forces of up to about 30 N in our preliminary experiments, so suture breakage is not a big problem when performed by hand. Using a robot, however, it is far more difficult due to the absence of haptic feedback and suture breakage is therefore more normal.

A. Experimental Set-up

The experimental set-up consists of a master and a slave device with virtually no time delay. The master device is an Omega 7 from Force Dimension which is a parallel haptic device with force feedback in three translational degrees of freedom and one degree of freedom in a pinching motion. An ABB IRB140 industrial robot with a force/torque sensor at the tip, the 100M40 from JR3, is used as the slave device.

The slave robot is controlled by *Robot Main Computer* and *Robot Axis Computer*. Joint angles, velocities, and local control parameters can be obtained from *Robot Main Computer* and *Robot Axis Computer* enables us to control each joint with position and velocity references, see [19]. The intermediate layer is implemented between *Robot Main Computer* and *Robot Axis Computer* by MATLAB Simulink and Real-Time Workshop. To simplify the analysis and interpretation of the experimental results the robot was constrained to a 1-DoF motion in the direction of the z -axis.

B. Experimental Results

Several experiments were performed to get a better understanding of the safety and awareness levels. We first find the characteristics of the suture by identifying the force needed to break it. It was measured to be approximately 30 N. To

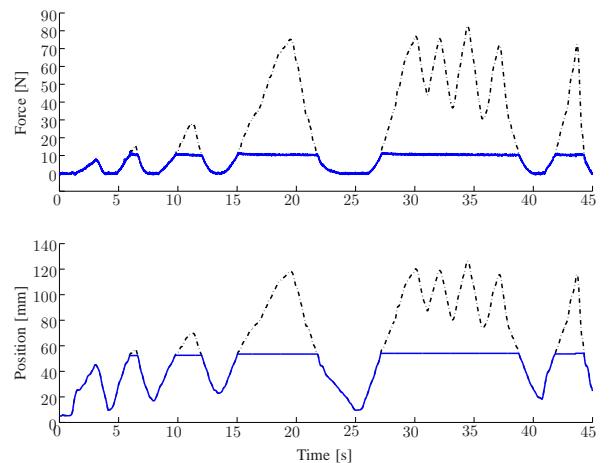


Fig. 5. The top graph shows the forces sensed at the suture (full, blue line) and the forces sent to the master (dotted, black line). The lower plot shows the proxy positions (full, blue line) which are given as a reference to the slave, and the master positions (dotted, black line).

prevent that we reach this suture breakage force, F_{lim} is set to 10 N. Since the master device only can apply a 12 N force, we scale down the force to one tenth. However, the \hat{F}_m illustrated in the figures is not scaled down so that we can easily compare it with F_s .

In Fig. 5 we see the forces applied to the master compared to the forces that act on the suture. We see that the forces that act on the suture are limited to approximately 10 N but the operator feels a force that is far stronger because of the additional awareness level. The lower plot shows the slave positions \hat{x}_s and master position x_m , and we see clearly that the force is proportional to the difference $x_m - \hat{x}_s$.

Fig. 6 shows the position force diagram for the master and slave robots. The top plot shows the master robot and we see that no force is applied to the robot when there is no force measured at the tip. When the suture force is below 10 N the only force that the operator feels is the **measured** force F_s . However, when the force exceeds 10 N, which happens at approximately $\hat{x}_s = 5.4$ cm, the second term in (1) adds a force to the master device, which can be clearly seen from Fig. 6. The second plot shows the position-force diagram for the slave manipulator and we see that the position of the slave is restricted, which also restricts the forces that are applied to the suture, which was the intention of the safety layer.

Because the relationship between the position x_m and the force \hat{F}_m is linear, the impedance perceived by the operator is considered as a stiffness. The stiffness transmitted to the operator is sharply changed from 330 N/m to 1000 N/m at 5.4 cm as shown in Fig. 6. As stated in [6], the perceptual sensitivity for the impedance variables can be used as a tool to detect a specific force. Since just noticeable difference (JND) of the stiffness variable is about 8 ~ 22% [20] and the ratio between two impedances is about 300%, the human operator can easily detect the F_{lim} .

Figure 7 illustrates what happens when the suture force is not sufficiently restricted. We see that the second time

¹ETHICON PDS II, polydioxanone, violet monofilament, 2-0 3 Ph. Eur., ETHICON LLC.

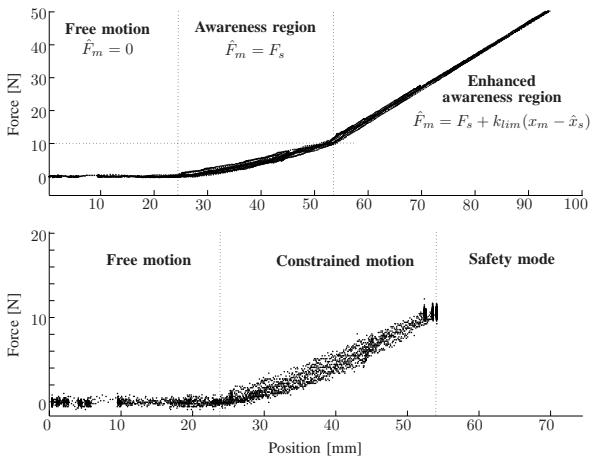


Fig. 6. The force-position diagrams for desired master force \hat{F}_m (top plot) and the measured slave force F_s (bottom plot).

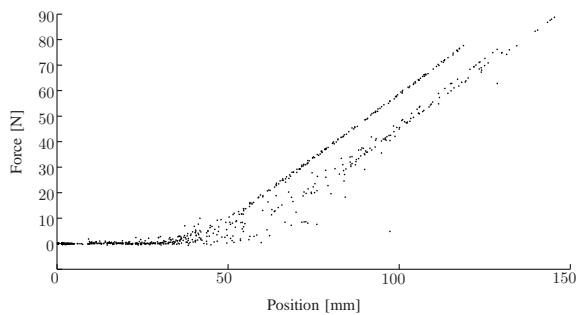


Fig. 7. The force-position diagram for desired master force \hat{F}_m when the forces applied to the suture are not sufficiently restricted. We see that the suture deforms. The two "paths" show the position-force relation before and after the suture has been deformed by the forces applied by the robot.

we move into the enhanced awareness region (the rightmost path) the suture is stretched out compared to the first time we moved into this region (the leftmost path). This is because the first time we moved into this region we did not restrict the suture forces which resulted in a deformed suture.

V. DISCUSSION

There are many ways to implement the intermediate layer to increase safety during suturing. In this section we will look at some ways to design sub-levels for increased safety and enhanced performance in suturing procedures, which is validated with experiments. We will also look at how these can be combined to get an overall improved performance of the system.

A. Awareness Level

To enhance the awareness of the operator a modified force feedback signal can be fed back to the haptic device. Using only the measured end-effector force F_s does not make the operator sufficiently aware of the forces that act on the suture. We therefore choose to enhance operator awareness by increasing the feedback force. This can be done either by scaling up the feedback force or by increasing the force when the measured end-effector force exceeds some limit.

Scaling up the feedback force \hat{F}_m in this way may prevent the operator from breaking the suture because she/he becomes more aware of the forces that the robot applies to the suture. The main problem with this approach is that the force feedback will to a certain extent become a disturbing factor because it becomes so large. Furthermore, there is nothing that impedes the surgeon from breaking the suture if enough force is applied.

B. Safety Level

To improve safety during suturing we choose to limit the forces that the operator can apply to the suture by modifying the slave reference x_s . The new slave reference \hat{x}_s is then constructed to limit the forces on the suture. The main problem with this type of limitations is that we do not want to limit the suture force F_s directly because this would lead to sharp boundaries and a very unnatural behavior. We therefore choose to restrict the velocity of the robot whenever the suture force reaches some limit. This restriction on the velocity can be represented by x_{lim} which denotes the maximum allowed distance from one sample to the next, and it is designed so that $x_{lim} \propto 1/F_s$. This set-up limits the speed of the slave robot as the measured force F_s is increased, but it is also helpful when limiting the force level to F_{lim} by decreasing x_{lim} . We find that this approach reduces the forces on the suture as required. However, it does not feel very natural for the operator because the robot does not follow the reference given by the master device, but it restricts the motion to guarantee that the suture force does not exceed the limit, F_{lim} . This behavior of the robot is not communicated back to the operator except through the visual feedback.

C. Safety Level with Additional Awareness

To overcome the problem of unnatural behavior in the previous section we add an awareness level with the intention of notifying the operator whenever the control system overrides the operator. Since we restrict the slave position within the safety level, a position difference arises between the master and slave whenever the motion of the slave is restricted. This difference can then be used to create an artificial force which makes the operator aware that the control system overrides his reference. We then modify the master force to be

$$\hat{F}_m = F_s + k_{lim}(x_m - \hat{x}_s)$$

so that the operator feels the force from the force sensor and in addition to a force that increases with the difference between the master and the slave.

When this is implemented together with the safety level in the previous section, this will improve performance in many ways. First of all, this will make the operator aware that some action is taken. When this is communicated back to the operator it makes the operation more natural and the operator seems to overcompensate less for the errors that he experiences through the visual feedback. It will also automatically reduce the difference between the master device and the slave robot leading to a smoother and more damped motion.

VI. CONCLUSION

In this paper, we propose a novel method for improving operator awareness and safety in telesurgical systems. We develop an intermediate layer within the two-port network representation and show how to design the awareness and safety layers for some well-known difficulties in the telesurgical systems.

The importance of both the operator awareness level and the safety level are discussed, and the architecture and design of the intermediate layers are studied in detail. The intermediate layer as implemented in this paper is composed of two levels; a safety level and an awareness level. The safety level produces a safe position reference for the slave robot and the awareness level transfers an artificially fabricated interaction force to the operator. The intermediate layer can be divided in several sub-layers or connected with other layers since both the input and the output are defined in same manner, i.e., as a two-port.

Two intermediate layers are designed to deal with specific problems commonly found in telesurgical systems; suture breakage and collision avoidance. The algorithms for both the awareness and safety levels are presented and the approach is validated through experiments where forces are applied to a suture by an industrial robot controlled by a haptic device. In the future, we are planning to demonstrate more complicated procedures in telesurgical system with dual-arm robots based on this concept.

APPENDIX

Algorithm of IL-LIM

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1  $x_{dist} = x_m - \hat{x}_{s,prev}$ 
2 if (  $(\|F_s\|_2 < F_{lim})$  or  $(x_{dist} \cdot F_s > 0)$  )
3   if ( $\|x_{dist}\|_2 < x_{lim}$ )
4      $\hat{x}_s = x_m$ 
5   else
6      $\hat{x}_s = \hat{x}_{s,prev} + \frac{x_{lim}}{\|x_{dist}\|_2} x_{dist}$ 
7   end
8    $\hat{F}_m = F_s$ 
9 else
10   $x_{dist,2} = x_{dist} - (x_{dist} \cdot \frac{F_s}{\|F_s\|_2}) \frac{F_s}{\|F_s\|_2}$ 
11  if ( $x_{dist,2} \neq 0$ )
12     $x_{dist,3} = \frac{x_{lim}}{\|x_{dist,2}\|_2} x_{dist,2}$ 
13  else
14     $x_{dist,3} = 0$ 
15  end
16  if ( $\|x_{dist,2}\|_2 < x_{lim}$ )
17     $\hat{x}_s = \hat{x}_{s,prev} + x_{dist,2}$ 
18  else
19     $\hat{x}_s = \hat{x}_{s,prev} + x_{dist,3}$ 
20  end
21   $\hat{F}_m = F_s + k_{lim}(x_m - \hat{x}_s)$ 
22 end

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Algorithm of IL-COL

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1  $x_{dist} = x_m - \hat{x}_{s,prev}$ 
2 if ( $distance(\mathcal{S}(x), \hat{x}_{s,prev}) < x_{thr}$ )
3    $\hat{x}_{s,prx} = \text{closest point of } \hat{x}_{s,prev} \text{ on } \mathcal{S}(x)$ 

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4   if( $(\nabla \mathcal{S}(\hat{x}_{s,prx}) \cdot x_{dist} < 0)$ 
5      $x_{dist,2} = x_{dist} - (x_{dist} \cdot \nabla \mathcal{S}(\hat{x}_{s,prx})) \nabla \mathcal{S}(\hat{x}_{s,prx})$ 
6     if ( $x_{dist,2} \neq 0$ )
7        $x_{dist,3} = \frac{x_{lim}}{\|x_{dist,2}\|_2} x_{dist,2}$ 
8     else
9        $x_{dist,3} = 0$ 
10    end
11    if ( $\|x_{dist}\|_2 < x_{lim}$ )
12       $\hat{x}_s = \hat{x}_{s,prev} + x_{dist,2}$ 
13    else
14       $\hat{x}_s = \hat{x}_{s,prev} + x_{dist,3}$ 
15    end
16  else
17     $\hat{x}_s = x_m$ 
18  end
19   $\hat{F}_m = F_s + k_{lim}(x_m - \hat{x}_s)$ 
20 else
21    $\hat{x}_s = x_m$ 
22    $\hat{F}_m = F_s$ 
23 end

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REFERENCES

- [1] G. Guthart and J. Salisbury Jr, "The intuitive™ telesurgery system: overview and application," in *Proc. IEEE Int. Conf. Rob. Aut.*, pp. 618–621, 2000.
- [2] D. Nio, R. Balm, S. Maartense, M. Guijt, and W. Bemelman, "The efficacy of robot-assisted versus conventional laparoscopic vascular anastomoses in an experimental model," *Eur. J. Vasc. Endovasc.*, vol. 27, no. 3, pp. 283–286, 2004.
- [3] T. Vidovszky, W. Smith, J. Ghosh, and M. Ali, "Robotic cholecystectomy: learning curve, advantages, and limitations," *J. Surg. Res.*, vol. 136, no. 2, pp. 172–178, 2006.
- [4] M. Kitagawa, D. Dokko, A. Okamura, and D. Yuh, "Effect of sensory substitution on suture-manipulation forces for robotic surgical systems," *J. Thorac. Cardiovasc. Sur.*, vol. 129, no. 1, pp. 151–158, 2005.
- [5] C. Reiley, T. Akinbiyi, D. Burschka, D. Chang, A. Okamura, and D. Yuh, "Effects of visual force feedback on robot-assisted surgical task performance," *J. Thorac. Cardiovasc. Sur.*, vol. 135, no. 1, pp. 196–202, 2008.
- [6] J. H. Cho, H. I. Son, M. Annerstedt, A. Robertsson, and R. Johansson, "Enhancement of human operator's perceptual sensitivity for telesurgical systems via polytopic system approach," in *Proc. BioRob'12*, pp. 75–80, June 2012.
- [7] C. Zilles and J. Salisbury, "A constraint-based god-object method for haptic display," in *Proc. IEEE/RSJ Int. Conf. Intel. Rob. Syst.*, pp. 146–151, 1995.
- [8] M. Ortega, S. Redon, and S. Coquillart, "A six degree-of-freedom god-object method for haptic display of rigid bodies with surface properties," *IEEE T. Vis. Comput. Gr.*, vol. 13, no. 3, pp. 458–469, 2007.
- [9] D. Ruspini, K. Kolarov, and O. Khatib, "The haptic display of complex graphical environments," in *Proc. 24th Ann. Conf. Computer graphics and interactive techniques*, pp. 345–352, 1997.
- [10] N. Hogan, "Controlling impedance at the man/machine interface," in *Proc. IEEE Int. Conf. Rob. Aut.*, pp. 1626–1631, 1989.
- [11] N. Hogan, "Impedance control: An approach to manipulation: Part I-theory, part II-implementation, part III-applications," *J. Dyn. Syst. Meas. Control*, vol. 107, no. 2, pp. 1–24, 1985.
- [12] O. Khatib, "Real-time obstacle avoidance for manipulators and mobile robots," *Int. J. Robot. Res.*, vol. 5, no. 1, pp. 90–98, 1986.
- [13] R. Johansson, M. Annerstedt, and A. Robertsson, "Stability of haptic obstacle avoidance and force interaction," in *Proc. IEEE/RSJ Int. Conf. Intel. Rob. Syst.*, pp. 3238–3243, 2009.
- [14] B. Hannaford, "A design framework for teleoperators with kinesthetic feedback," *IEEE T. Robotic. Autom.*, vol. 5, no. 4, pp. 426–434, 1989.
- [15] D. Lee and M. Spong, "Passive bilateral teleoperation with constant time delay," *IEEE T. Robotics*, vol. 22, no. 2, pp. 269–281, 2006.
- [16] P. Hokayem and M. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, 2006.

- [17] J. Ryu, D. Kwon, and B. Hannaford, "Stable teleoperation with time-domain passivity control," *IEEE T. Robotic. Autom.*, vol. 20, no. 2, pp. 365–373, 2004.
- [18] J. Ryu, Y. Kim, and B. Hannaford, "Sampled-and continuous-time passivity and stability of virtual environments," *IEEE T. Robotics*, vol. 20, no. 4, pp. 772–776, 2004.
- [19] A. Blomdell, I. Dressler, K. Nilsson, and A. Robertsson, "Flexible application development and high-performance motion control based on external sensing and reconfiguration of ABB industrial robot controllers," in *Proc. IEEE Int. Conf. Rob. Aut.*, 2010.
- [20] L. A. Jones, "Kinesthetic sensing," in *Human and Machine Haptics*, MIT Press, 2000.