A human activity-aware shared control solution for medical human–robot interaction

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Abstract
Purpose – The purpose of this paper is to develop a human activity-aware adaptive shared control solution for human–robot interaction in surgical operation. Hands-on control and teleoperation are two main procedures switched frequently in teleoperated minimally invasive surgery (MIS). The detailed human activity in the procedures can be defined and recognized using the sensor information. In this paper, a novel continuous adaptive shared control method is proposed for manipulators with Cartesian impedance control in the surgical scenario.

Design/methodology/approach – A human activity-aware shared control solution by adjusting the weight function is introduced to achieve smooth transition among different human activities, including hands-on control and teleoperation. Instead of introducing various controllers and switching among them during the surgical procedures, the proposed solution integrated all the human activity-based controllers into a single controller and the transition among the procedures is smooth and stable. The effectiveness of the proposed control approach was verified in a lab setup environment. The results prove that the robot behavior is stable and smooth. The algorithm is feasible and can achieve a human activity-aware adaptive shared control solution for human–robot interaction in surgical operation.

Findings – Based on the experiment, the results confirm that the proposed human activity-aware adaptive shared control solution can switch the device behavior automatically using the real-time sensor information. The transition between different activities is smooth and stable.

Practical implications – For teleoperated surgical applications, the proposed method integrated different controllers for various human activities into a single controller by recognizing the activities using the real-time sensor information and the transition between different procedures is smooth and stable. It eases the surgical work for the surgeon and enhances the safety during the transition of control modes. The presented scheme provides a general solution to address the switching of working procedures in teleoperated MIS.

Originality/value – To the best of the authors’ knowledge, this paper is the first to propose human activity-aware adaptive shared control solution for human–robot interaction in surgical operations.

Keywords Human activity aware, Adaptive shared control, Remote center of motion, Safe human–robot interaction, Surgical operation

Paper type Research paper

1. Introduction

The advantages of introducing minimally invasive surgery (MIS) in the operating room have significantly stimulated the spread of teleoperated surgical robots in the past decades (Lanfranco et al., 2004). Teleoperated medical robots could offer greater surgical precision, better range of motion, raised dexterity and magnified visualization for the operators. In
“Teleoperation”: the movement of the robot manipulator is driven through the remote device with a planned mapping (Su et al., 2021a, 2021b). Both procedures are activated and their corresponding controllers switch based on the actual human activity (Qi et al., 2020) in the surgical operations, for example, the neuroArm (Sutherland et al., 2008), the Da Vinci robot (Guthart and Salisbury, 2000) and the MiroSurge (Hagn et al., 2010). In the workflow of teleoperated MIS (Su et al., 2020a, 2020b), the surgeon requires to switch from one procedure to another, which is usually achieved with difficulty by switching modes and may produce sharp interventions in the current motion of the robot manipulator. The safety of the transition phase is required during the execution of the surgery. Mirko et al. proposed switching from one procedure to the following via a graphical user interface (GUI) (Comparetti et al., 2014). However, it diverts the surgeon’s attention from the ongoing surgery. More importantly, a simple switch can create a jump in the controller, leading to instability.

Actually, the detailed human activity in the procedures can be defined and recognized using sensor information. We can integrate all human activities related to controllers into a single controller rather than introduce various controllers and switch among them during surgical procedures. It is feasible to implement transition between the procedures using shared control. In addition to the safety during the transition of control modes, this can further ease the surgical work for the surgeon by increasing the intelligence of the medical devices. In Li et al. (2017), a continuous adaptive control method integrates two separate control modes into a single controller, achieving a safe and smooth transition. Therefore, it is also feasible to accomplish a human activity-aware adaptive shared control solution for human–robot interaction in a surgical operation.

This paper introduced the idea and proposed a novel human activity-aware adaptive shared control method that integrates different controllers, including hands-on control and teleoperation, into a single controller. Human activities recognition makes the system more intelligent, but a simple switch will cause instability and a jump between behaviors. The main challenge is to guarantee smooth and safe switching between different controllers. Shared control is used to investigate human activity-based control, which has the advantage of being continuous and stable, enabling natural and smooth human–robot interaction.

First, the detailed human activity in the procedures can be defined and recognized using the sensor information. Then, control method automatically transits between both the modes without human involvement, such as GUI. The robot can be controlled by hand and teleoperation during the transition based on real-time human activities. A human activity-aware shared control solution by adjusting the weight function is introduced to achieve a smooth transition among different human activities. The proposed solution integrated all the human activities-based controllers into a single controller rather than introducing various controllers and switching among them during the surgical procedures. And the transition between the procedures is smooth and stable. The effectiveness of the presented control method was verified in a laboratory setup environment. The results demonstrate that the behavior of the robot is stable and smooth. The algorithm is viable for accomplishing a human activity-aware adaptive shared control solution for medical human–robot interaction.

This paper is organized as follows: the model of the manipulator and the challenges are presented in Section 2. In Section 3, the proposed human activity-aware adaptive control schemes are illustrated. The system description and performance evaluation are shown in Section 4. And conclusions and discussions are provided in Section 5.

### 2. Preliminary and methodology

#### 2.1 Modeling the serial manipulator

Industrial robots have gained increasing research attention in the past years. The accuracy and robustness have been improved with prominent performance. It is worth mentioning that the general serial robots have been popularized in the operating room because of its advantages in flexibility and budget friendliness. The objective of this research is to transfer the generalized robots to the medical scenario with human–robot interaction. It has been well known that the dynamic model of n-degrees of freedom (DoF) medical robot manipulator can be expressed as:

\[ M(q)\ddot{q} + C(q, \dot{q})q + g(q) = \tau_c - \tau_{\text{ext}} \]

where \( q \in \mathbb{R}^n \) is the joint values, \( M(q) \in \mathbb{R}^{n \times n} \) is the inertia matrix, \( C(q, \dot{q}) \in \mathbb{R}^{n \times n} \) is a matrix representing the coriolis and centrifugal effects and \( g(q) \in \mathbb{R}^n \) is the gravity torques vector. The torque vectors \( \tau_c \in \mathbb{R}^n \) and \( \tau_{\text{ext}} \in \mathbb{R}^n \) represent the control torques and the external torque vectors, respectively. This can be the general expression for most of the robot manipulators.

On the other side, a torque control mode can be used to move and control the robot tool. To drive the movement of the manipulator tool, in general, the torque controller can be defined as:

\[ \tau_c = \dot{C}(q, \dot{q})q + g(q) + \tau_d \]

where \( \dot{C}(q, \dot{q}) \in \mathbb{R}^{n \times n} \) and \( g(q) \in \mathbb{R}^n \) are estimated compensation torques for the forces, such as gravity term and \( \tau_d \in \mathbb{R}^n \) is the control term used to manipulate the tool for the task performing.

#### 2.2 Remote center of motion

For medical applications, surgical robot has been developed and involved in many scenarios because of their benefits in flexibility and accuracy. In particular, the surgical robot reduces the size of the incision and makes it faster for the patient to recover from the pain. Hence, different applications have been developed in this area, no matter for research and clinical study. Even for the COVID–19, many redundant serial manipulators have been introduced and designed to avoid spreading the virus. As shown in Figure 1, the surgical instrument passes through the small incision, which means that the surgical operation should be conducted under the motion constraint generated by the designed point. This is related to a constrained motion for medical operation.

To perform the surgical operation, an online motion control scheme should be adopted to maintain the motion constraint, avoiding huge force interaction on the small incision. It can be seen from Figure 1, given the desired tool placement for the
manipulator control, the force used to move the tool from actual placement to the desired location should be counted and optimized. First, the actual instrument placement can be defined with the operational coordinates $X = [\mathbf{X}_P, \mathbf{X}_R]^T \in \mathbb{R}^6$, including the actual tool tip positions $\mathbf{X}_P = [x, y, z]$ and the actual tool orientation expressed by Euler angles $\mathbf{X}_R = [\alpha, \beta, \gamma]$. $\mathbf{X}_d = [\mathbf{X}_{Pd}, \mathbf{X}_{Rd}]^T \in \mathbb{R}^6$ is the desired tip pose, where $\mathbf{X}_{Pd} = [x_d, y_d, z_d]$ is the desired Cartesian position given by the master device and the desired orientation $\mathbf{X}_{Rd} = [\alpha_d, \beta_d, \gamma_d]$ is calculated based on $\mathbf{X}_P$ online to guarantee the tip going through the trocar position $\mathbf{P}_t = [x_t, y_t, z_t]$ during the movement, as follows:

In this paper, $\theta = \arctan \frac{u_{d,z}}{u_{d,y}}$ can be used to calculate the rotation angle $\theta$ (see Figure 1) between the actual tool direction $\mathbf{u}$ and the desired tool direction $\mathbf{u}_d$. The rotation axis $\mathbf{u}_r = [u_z, u_y, u_x]$ from $\mathbf{u}$ to $\mathbf{u}_d$ can be described with $\mathbf{u}_r = \frac{u_d \times \mathbf{u}}{|u_d \times \mathbf{u}|}$. A skew-symmetric matrix $\Gamma$ is introduced to calculate the desired orientation matrix, as:

$$\Gamma = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix}$$

Then the desired orientation matrix $\mathbf{R}_d$ can be expressed as:

$$\mathbf{R}_d = \mathbf{I} + \Gamma \sin(\theta) + 2\Gamma^2 \sin^2\left(\frac{\theta}{2}\right) \cdot \mathbf{R}$$

where $\mathbf{R}$ is the actual rotation matrix. It is easy to get $\mathbf{X}_{Rd}$ with Euler transformation from rotation matrix $\mathbf{R}_d$. To reach the desired tip pose $\mathbf{X}_{td}$ task-space impedance control, $\mathbf{\tau}_T \in \mathbb{R}^6$, as used in Dietrich et al. (2012) is introduced as:

$$\mathbf{\tau}_T = \mathbf{J}^T \left( \frac{\partial \mathbf{V}(\mathbf{q})}{\partial \mathbf{X}} \right)^T - \mathbf{D}_x \mathbf{X}$$

where $\mathbf{J} \in \mathbb{R}^{6 \times n}$ is the Jacobian matrix and $\mathbf{D}_x \in \mathbb{R}^{6 \times 6}$ is the damping matrix. In this paper, we assume that the surgical robot is far from its singularity and the pseudoinverse of $\mathbf{J}$ exists to ease the calculation.

### 2.3 Human activity-aware adaptive control scheme
The detailed human activity in the procedures can be defined and identified by sensor information. Generally, it is essential to introduce various controllers and to switch among them during surgical procedures. A human activity-aware shared control solution is introduced via adjusting the weight function to achieve a smooth transition between different human activities, including hands-on control and teleoperation. In place of introducing various controllers and switching among them during the surgical procedures (Figure 2), the proposed solution integrated all the human activities-based controllers into one controller and the transition during the procedures is smooth and stable. For simplification, the torque control term for the different procedures of the teleoperated MIS is defined and expressed as follows:

#### 2.3.1 Hands-on control
The human operators move the robot manipulator by exerting hand forces on the robot arm. In this procedure, the robot behaves in a passive way and can be driven by human intention and movement. Usually, the robot manipulator does not
provide the main power. Hence, the torque controller of hands-on control can be expressed as:

$$\tau_d = -D_H \dot{X}$$

where $D_H \in \mathbb{R}^{6 \times 6}$ is the diagonal damping matrix and $X \in \mathbb{R}^6$ is the actual Cartesian velocity. A damping term is used to smooth the motion of the manipulator.

### 2.3.2 Teleoperation

Teleoperation indicates the operation of a surgical manipulator at a distance. It is similar in meaning to the phrase “remote control.” The robot manipulator is driven to follow the desired trajectory mapped from the haptic device at the remote site. At the same time, the external force does not intervene in the accuracy of the surgical tasks. Hence, the torque controller of teleoperation (remote control) can be expressed as:

$$\tau_d = \tau_f - \tau_H,$$

where $\tau_f = \hat{\tau}_{\text{ext}} \in \mathbb{R}^6$ is the filtered torque from external torque sensors.

For the whole surgical operation procedures, the human activity of using device behavior is not totally separated by the boundary between the outside and inside the patients’ body. And the detailed human activity in the procedures can be defined and recognized using sensor information. As shown in Figure 3, hands-on control is activated in the whole area outside the abdomen in Figure 3(a). In contrast, teleoperation is adopted near the surgical target area in Figure 3(c). There should be a transition area between the two specified areas in Figure 3(b), where the surgical manipulator should be possibly controlled by both hands-on and teleoperation. This means that both hands and a remote haptic device in the transition area can move the surgical manipulator. The transition between the two procedures should be smooth and safe. Therefore, a human activity-aware shared control solution is introduced by adjusting the weight function to smooth the transition between different human activities, including hands-on control and teleoperation.

This paper divides the surgical robot workspace into three parts and proposes an adaptive controller to automatically switch control procedures among the three areas without GUI commands or any other equipment operation. To distinguish which area the tool tip is in and recognize the human activity in the procedures, we assume the transition area is a part of the sphere. Its origin is the trocar position $P_t$ and its radius is $l$. Then, a parameter $d$ is introduced as:

$$d = (X(q) - P_t) \cdot \dot{u},$$

where $X(q)$ is the actual Cartesian position and $\dot{u}$ is the actual tip direction. The control mode can be defined in Table 1.

To achieve a smooth and safe transition during the shared control procedure, the adaptive weight function is established based on the transition region:

$$W(d) = \left(1 - \cos(\min[\max(0, d/l) \times \pi/\beta]) \right)^\sigma,$$

where $\sigma \in \mathbb{R}^+$ is a positive index for the adaptive weight distribution. The corresponding illustration of the weight distribution can be seen in Figure 4. The whole control diagram of this work is described in Figure 5. The teleoperation mode and hands-on control mode are integrated in the same controller. An impedance control is implemented to achieve the switching mode in a smooth way.

### 3. Experimental demonstration and performance analysis

#### 3.1 System description

The system setup for the demonstration of a lab setup environment is shown in Figure 6. It consists of a surgical robot manipulator, a remote haptic device and an endoscopic camera.

### Table 1

<table>
<thead>
<tr>
<th>$d$</th>
<th>Control mode</th>
<th>Torque formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d \leq 0$</td>
<td>Hands-on</td>
<td>$\tau_d = -D_H \dot{X}$</td>
</tr>
<tr>
<td>$0 \leq d \leq l$</td>
<td>Adaptive share control</td>
<td>$\tau_d = W(d)(\tau_f - \tau_H) - (1 - W(d))D_H \dot{X}$</td>
</tr>
<tr>
<td>$d \geq l$</td>
<td>Teleoperation</td>
<td>$\tau_d = \tau_f - \tau_H$</td>
</tr>
</tbody>
</table>

Notes: $l$ is the radius of the transition area; $W(d) \in \mathbb{R}$ is the weight function and $0 \leq W(d) \leq 1$.
All the devices are controlled with a control computer, which runs on a real-time Xenomai-patched ubuntu operating system. The system communication is established using a robot operating system. A three-dimensional-printed human patient phantom is used to provide the remote center of motion (RCM) constraint.

### 3.2 Experimental protocol

Two human operators have enrolled to set up the experimental scenario with the developed teleoperated surgical operational system. One user is responsible for directing the movement of the surgical instruments by hand and the other operator is responsible for the teleoperation of the surgical operational scenario.

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**Figure 4** Illustration of weight function $W(d)$, where $d = (\mathbf{X}(\mathbf{q}) - \mathbf{P}_T) \cdot \mathbf{u} \in R$

**Figure 5** Block diagram of the adaptive control scheme

Notes: (a) $W(d)$ transits smoothly between 0 and 1, and $W(d) = 0$ and $W(d) = 1$ correspond to the modes of hands-on control and teleoperation, respectively; (b) $\sigma$ determines the distribution shape of the weight distribution during the transition procedure between hands-on control and teleoperation.
tasks. The robot’s behavior is automatically switched based on the actual human activities by detecting the tool tip position. Following the proposed scene in Figure 3, the two users test hands-on and teleoperation in three different areas (I, II and III). In the experiment, \( l = 0.1 \text{ m}, \sigma = 3, D_H = \text{diag} \{5, 5, 5, 0.3, 0.3, 0.3\} \text{ Ns/m}, D_X = \text{diag} \{3000, 3000, 3000, 300, 300, 300\} \text{ Ns/m} \text{ and } K_X = \text{diag} \{30, 30, 30, 3.5, 3.5, 3.5\} \text{ N/m.} \) During the whole procedure, hands-on force \( F_H = (F_{Hx}, F_{Hy}, F_{Hz}) \), teleoperation force \( F_T = (F_{Tx}, F_{Ty}, F_{Tz}) \) and the tool tip trajectory \( X = (x, y, z) \) are collected. The parameter \( d \) and adaptive weight \( W \) are also recorded.

As shown in Figure 7, the hands-on force \( F_H \) represents human tendency and \( d \) and \( F_T \) illustrate teleoperation tendency. \( X \) is the actual tool tip trajectory. In the first procedure (I), the tool tip trajectory is determined by only hand force. And in the teleoperation procedure, the hands-on force does not affect the trajectory. In the adaptive shared control procedure (II), both hands-on and teleoperation work. The proposed controller can flexibly switch the modes in the transition area by monitoring the variation of tool tip position.

4. Conclusion and discussion

Instead of designing multiple controllers and switching between them using GUI, this paper developed a continuous adaptive control method with a unified formulation that integrates hands-on control and teleoperation into a single controller for teleoperated surgical operation. A human activity-aware shared control solution is introduced by adjusting the weight function to achieve a smooth transition between different human activities, including hands-on control and teleoperation (Luo et al., 2021). The clinical scenarios are that the teleoperator does not successfully conduct the surgery or something unexpected happens during the surgery. Then, hands-on control is activated to lead the robot by exerting forces on the robot directly and putting the surgical tip out from the patient’s abdomen, thus guaranteeing the safety of the surgery. The transition between the surgical procedures is smooth and stable. It eases the surgical work for the surgeon and improves safety during the transition of control modes. The presented scheme provides a general solution to address the transition of working procedures in teleoperated surgery.

Instead of introducing various controllers (Chen and Qiao, 2020a, 2020b) and switching among them during the surgical procedures, the proposed solution integrated all the human activities-based controllers into a single controller. The effectiveness of the proposed control approach was verified in a lab setup environment. The results prove that the robot’s behavior is stable and smooth. The algorithm is feasible to achieve a human activity-aware adaptive shared control solution for human–robot interaction in surgical operations.

However, in this work, we adopt a torque sensor to measure the hand force and ignore the other possible external forces, which is not adequate for complete clinical application. In the following work, we would install a 6 dimensional force sensor on the tool tip to achieve the hands-on force measurement and adopt hand force magnitude to transit between hands-on and teleoperation mode. In our future work, sensor fusion and deep
learning will be used to recognize human activities (Qi et al., 2021a; Qi et al., 2021b). Complex environments and case studies will be considered to make the solutions more reliable and natural (Su et al., 2021a, 2021b; Chen and Qiao, 2020a).

References


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