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Conceptual design of force reflection control for teleoperated bone surgery

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Abstract: Bilateral control of teleoperated robots still poses a challenge, especially if environment properties vary over a large degree. Most currently available systems do not provide force feedback and consequently surgeons still have to estimate contact forces predominantly visually. During drilling or milling in bone surgery, visual estimation is virtually impossible due to hardly any deformations. However, the force progression contains important complimentary information for the surgeon. Therefore, a concept for a force-reflecting controller for drilling or milling during teleoperated bone surgery was developed and tested on a one degree of freedom (DOF) test setup. First, the desired behavior and control architectures were derived based on the context of bone surgery. The resulting controller combines three control architectures in a switching controller, depending on the tool actuation and environment properties. Experimental results with a 1-DOF test setup showed the desired control and switching behavior, while remaining stable. Therefore, the developed control concept seems promising for teleoperated bone surgery.

Keywords: bilateral control; haptics; robotic surgery.

Introduction

During conventional surgery, surgeons rely on multimodal sensory information from visual, auditory and haptic signals. During robotic surgery the haptic information channel is often lost, such that surgeons have to dominantly rely on their visual sense to estimate forces applied on the environment [1, 2]. While visual estimation is feasible during soft tissue surgery, it is virtually impossible during drilling or milling in bone surgery, as there are hardly any deformations. Nevertheless, during a drilling for a pedicle screw placement, for example, there is a distinct force progression which contains important complementary information about tissue types for the surgeon [3].

Teleoperation is promising because it is the only system variant which can improve motion accuracy by scaling [2]. One reason for the limited utilization of haptic interfaces lies in challenges such as control loop stability. Bilateral teleoperation controllers which are tuned to remain stable in soft environments can turn instable when in contact with bone and vice versa [1]. While classical control approaches do not adapt to the environment, operator or task characteristics online, EOT-adapted (environment, operator, task) controllers use online gained knowledge for improvements [4]. However, a tradeoff between transparency and stability persists [4–6].

As stability over a wide range of stiffness such as during bone surgery poses a challenge, stability is ensured for example by using a passivity observer [7], by combining multiple controllers for different stiffness ranges [5, 6], or simply switching off the controller for hard contacts [8]. The contribution of this paper is a control architecture specifically for teleoperated drilling or milling, based on requirements derived from the context of bone surgery.

Conceptual controller design

During surgical drilling or milling, the activation of the tool can be used as a fundamental indication of intentions of the surgeon. In case the tool is switched off while making contact to hard surfaces (e.g., bone), it is expected, that the surgeon does not want to penetrate the tissue. The slave should stop in front of the hard contact after the first encounter in order to prevent damage. Nevertheless, the surgeon should be made aware of the fact that he/she moved the device against a stiff structure, which should be displayed to him/her by a hard virtual wall. If the tool used is switched on, it is expected that the surgeon wants to remove the tissue (e.g., bone) and the slave should penetrate the tissue while remaining stable. Encountered environments (i.e., compact and cancellous bone) should be reflected, such that the surgeon is able to differentiate

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between them. Additionally, the drilling/milling velocity of the slave should be limited to avoid excessive milling forces or temperature rise which can lead to bone damage [9]. However, when moving in free space or soft environments, the surgeon should feel the lowest possible resistance forces or the force should be mirrored back to the surgeon as accurately as possible, respectively, independent of the tool status.

To achieve the desired behavior, a design based on a switching controller inspired by Refs. [5, 6] was used. For free space movements and soft environments, independent of the tool status, a Direct Force Reflection (DFR) controller was chosen. DFR is a widely used control architecture, where position commands are sent from master to slave and forces measured between slave and environment are sent back to the master [7]. DFR is attributed with good tracking (as long as the time delay is low), a correct stiffness perception as well as a negligible position drift [10]. However, stability problems are encountered in hard contacts [7]. Therefore, in case a hard contact is encountered, with a deactivated tool, an architecture based on the widely used Position Error Based (PEB) control architecture was used. In PEB control, positions between master and slave are exchanged and a force is fed back based on the position error (i.e., virtual spring). A disadvantage thereof is that the operator feels the dynamics of the slave, which is why it is not suitable for free space movements and soft environments. However, PEB's inherent passivity makes it suitable for hard contacts [7]. The classic PEB control scheme was only slightly adapted so that the slave stops in front of a hard contact after detection. To reflect the environment more accurately, if the tool is switched on, while maintaining stability in hard contact, an adapted Stiffness Reflection (SR) control was chosen (Figure 1). Even though originally the authors claimed that stability is guaranteed since SR decouples the two control loops, estimation error and lag can lead to instability in practice [8]. SR was further extended by a velocity limiter, which is activated for hard material (i.e., compact bone) to avoid bone damage, and deactivated for softer materials (i.e., cancellous bone). The controller is changed back to DFR only if there is a change to motion in free space. Table 1 summarizes the desired control behaviors and chosen controllers based on tool status and environment.

While the tool is switched off, the environment stiffness $k_{e,\,\mathrm{off}}$ to switch between controllers is estimated based on the environment force f_e and the penetration depth Δx for each time step $t_i = \Delta T \times i$ with $\Delta T = 0.001$ s by

$$k_{e,\mathrm{off},i} = \frac{f_e}{\Delta x_s} \tag{1}$$

Since no removal of material is expected. Additionally, values are weighted based on the penetration depth Δx.

$$g_{\mathrm{off},i} = g_{\Delta x,i} = \max\left(0,\ 1 - e^{0.01\,\mathrm{mm} - \Delta x}\right) \tag{2}$$

If the tool is switched on, the environment stiffness $k_{e,\,\mathrm{on}}$ is estimated by the time derivative of the environment force and the velocity of the slave, as also suggested by Ref. [8].

$$k_{e,\mathrm{on},i} = \frac{\dot{f}_e}{\dot{x}_s} \tag{3}$$

Subsequently, values are weighted depending on the derivation of position and force (x and fe).

$$g_{\dot{x},i} = \max\left(0,\ 1 - e^{\left(\frac{0.01\,\frac{mm}{s} - \dot{\mathrm{x}}}{20\,\frac{mm}{s}}\right)}\right) \tag{4}$$

$$g_{\dot{f}_e,i} = \max\left(0,\ 1 - e^{\left(\frac{0.01\frac{N}{s} - \dot{f}_e}{20\frac{N}{s}}\right)}\right)\Bigg) \tag{5}$$

$$g_{\mathrm{on},i} = g_{\dot{x},i} \times\ g_{f,i} \tag{6}$$

Finally, the exponentially smoothed weighted average k_e is calculated by Eq. (7) and (8) with $N = 2000$, $\alpha_{\mathrm{off}} = 0.2$ and $\alpha_{\mathrm{on}} = 0.05$ for the tool switched off or on, respectively.

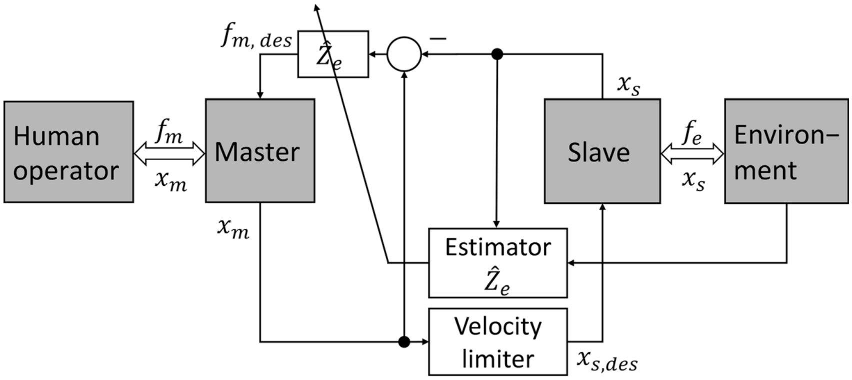

Figure 1: Adapted Stiffness Reflection (SR) control with additional velocity limiter. (f_m: force master, $f_{m,\,des}$: desired force master, x_m: position master, f_e: force environment, x_s: position slave, $x_{s,\,des}$: desired position slave, $\hat{Z}_e$: estimated environment impedance), local controllers of master and slave take care of desired values.

Table 1: Desired control behavior and controller depending on tool status and environment.

Tool status	Environment	Desired control behavior	Controller
Off	Free space	– Lowest possible resistance force	DFR
	Soft	– Mirror force as accurately as possible	DFR
	Hard	– After detection of a hard contact the slave should stop in front of it	PEB (adapted)
On	Free space	– Lowest possible resistance force	DFR
	Soft	– Mirror force as accurately as possible	DFR
	Hard	– Penetrate tissue and reflect encountered environments such that environments (i.e., compact and cancellous bone) can be differentiated – Limit drilling/milling velocity to avoid bone damage for hard environments	SR (adapted)

$$k_{e,\,\mathrm{off}} = \frac{\sum_{m=0}^{N-1} k_{e,\,\mathrm{off},\,i-m} \times g_{\mathrm{off},\,i-m} \times (1-\alpha_{\mathrm{off}})^m}{\sum_{m=0}^{N-1} g_{\mathrm{off},\,i-m} \times (1-\alpha_{\mathrm{off}})^m} \quad (7)$$

$$k_{e,\,\mathrm{on}} = \frac{\sum_{m=0}^{N-1} k_{e,\,\mathrm{on},\,i-m} \times g_{\mathrm{on},\,i-m} \times (1-\alpha_{\mathrm{on}})^m}{\sum_{m=0}^{N-1} g_{\mathrm{on},\,i-m} \times (1-\alpha_{\mathrm{on}})^m} \quad (8)$$

To classify the different contact situations, first a force hysteresis of $f_{e,\mathrm{th}} = 0.4 \pm 0.1$ N is checked to decide whether there is contact with the environment or not. Following, a hysteresis of $k_{e,\mathrm{th}} = 1 \pm 0.1$ N/mm is used to distinguish between soft and hard contacts (compare [7, 8, 11]). Additionally, stiffness for master force calculation is only modified during movements to smoothen the fed back force.

Experimental setup

The proposed method was implemented on the real time development processor board DS1006 (dSpace, Paderborn, Germany) and the real-time control software QUARC (Quanser, Markham, ON Canada) in association with Matlab Simulink (The Mathworks Inc., Natick, MA, USA) connected by an RS-422 connection (Figure 2). An omega.6 (Force Dimension, Nyon, Switzerland) haptic device, controlled to move in 1 degree of freedom (DOF), was used as master device. The slave consisted of a brushless EC motor with a planetary gear and encoder (Maxon Motor AG, Sachseln, Switzerland) and the F/T-Sensor Gamma SI-130-10 (ATI Industrial Automation, Apex, NC, USA). A capstan drive was used for movement conversion and an adapter for different springs and a friction pairing replicating the force profile of [3] were manufactured to simulate different contact situations. To compensate for latencies, due to the design of

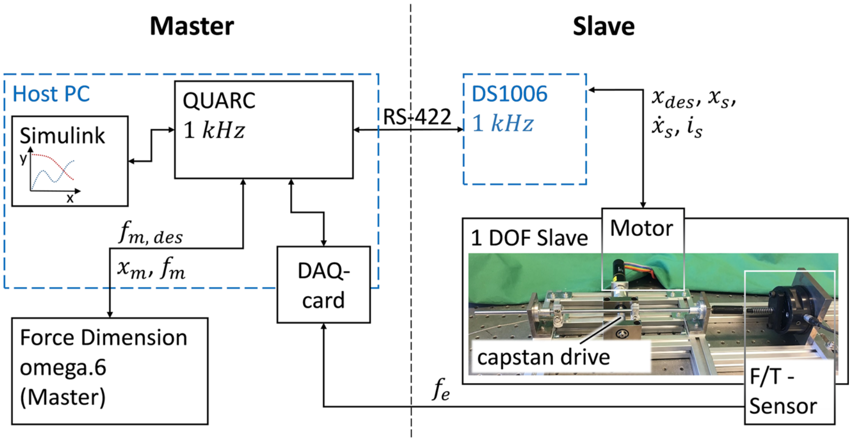

Figure 2: Schematic representation of the test setup. ($f_{m,\,\mathrm{des}}$: desired force master, x_m: position master, f_m: set force master, f_e: force environment, x_s: position slave, $\dot{x}_s$: velocity slave, $x_{s,\,\mathrm{des}}$: desired position slave, i_s: slave motor current), local controllers of master and slave take care of desired values.

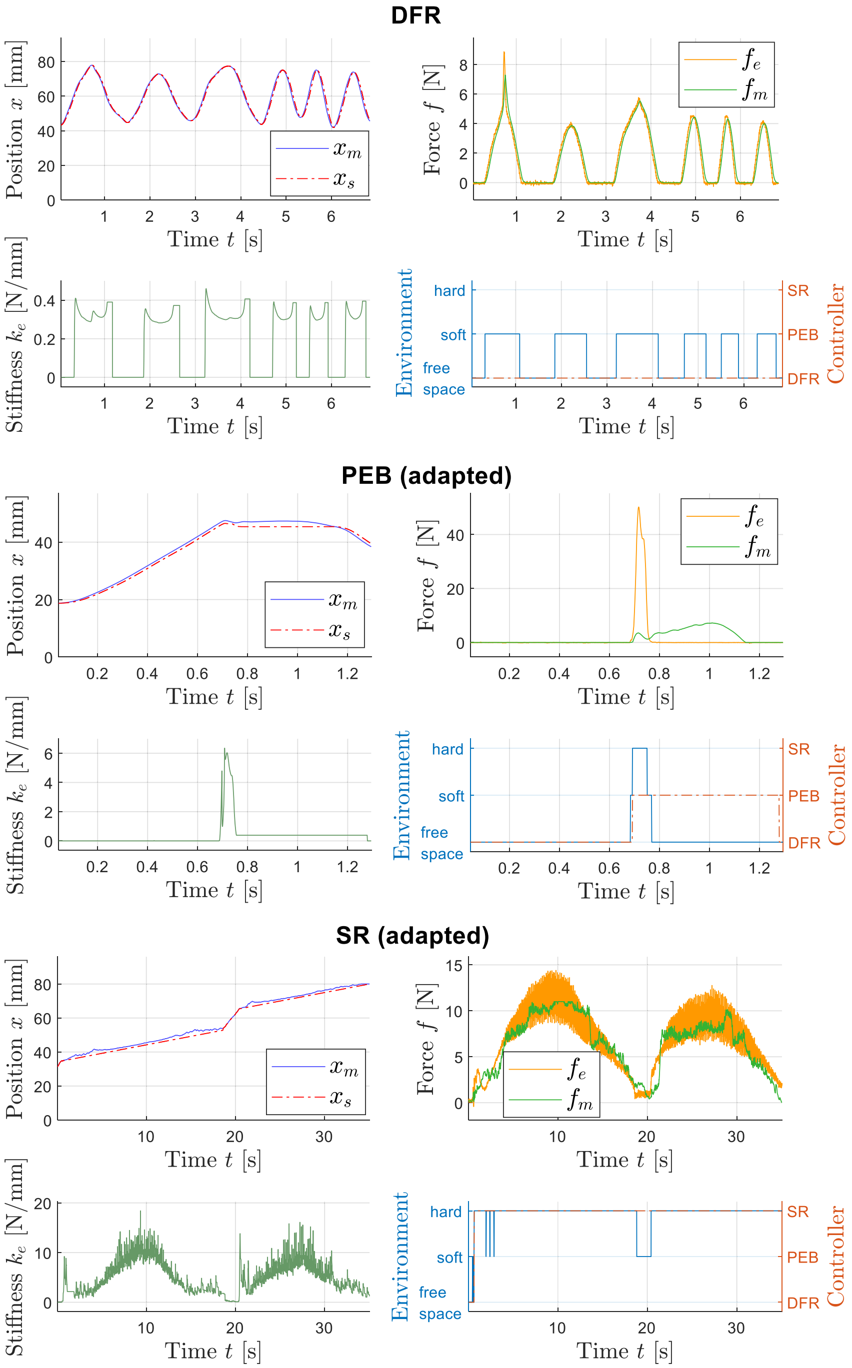

Figure 3: Experimental results with the test setup. (x_m: position master, x_s: position slave, f_m: set force master, f_e: force environment, k_e: environment stiffness).

the setup, an additional estimation of the contact force of the slave based on the slave motor current and an estimation of the slave position on the master side was implemented. Interaction with a spring ($k = 0.239$ N/mm) was used to evaluate control in free space and soft environments. Movement of the slave against a hard contact (>20 N/mm) with a deactivated tool variable was used to test PEB (adapted). The manufactured friction pairing which replicates the force profile of [3] served to evaluate SR (adapted).

Results

Figure 3 illustrates results obtained with the test setup. During interaction with a soft spring (Figure 3, DFR), the slave closely followed the master and the force was accurately replicated at the master side, while stiffness estimation was slightly higher than the spring stiffness of 0.239 N/mm. The contact was correctly classified as free space or soft environment.

Movement of the slave against a hard contact (>20 N/mm) with a deactivated tool variable was used to test PEB (adapted) (Figure 3, PEB). The slave followed the master until the environment was classified as hard at first contact ($t \approx 0.7$ s). Following, the slave stopped in front of the hard contact and a force was displayed at the master side to push the operator back to the slave position (0.7 s < t < 1.1 s). When moving out of the hard contact the slave started following the master again.

Interaction of SR (adapted) was tested with an activated tool variable and a manufactured friction pairing which replicates the force profile of [3] (Figure 3, SR). At first contact the environment was classified as hard and the velocity was limited ($t \approx 1$ s). For the short transition section (19 s < t < 21 s) the velocity limit was deactivated before it was activated again ($t \approx 21$ s) for the second force and stiffness peak. The force set at the master (f_m) roughly followed the force profile, however, since the stiffness and not the force is replicated this depends strongly on the interaction of the operator with the master device. The oscillations observed in the environment force f_e due to friction between the two components, which is likely to be observed during drilling or milling of bone, however, did not destabilize the system.

Discussion and conclusion

In this paper, a control approach for haptic feedback during teleoperated drilling or milling was developed based on a switching controller similar to Ref. [5, 6]. The controller switches between three architectures, namely DFR, PEB (adapted), and SR (adapted), depending on the activation of the tool and the environment properties. The controller was implemented on a 1-DOF test platform to evaluate the proposed approach. The experimental results showed the desired behavior and the system remained stable during the experiments.

Next steps of our ongoing research will be the implementation of the controller in combination with a 3-DOF milling robot to evaluate its performance under more realistic conditions.

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