Teleoperation of surgical robot using force feedback

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Abstract—**Haptic feedback is a way of transferring information to the user via the sense of touch, usually through an input device the user gives commands with. This makes it ideal for teleoperating tasks requiring precision in applied force, robotic minimally invasive surgery (MIS) being a prime example. Currently, haptic feedback in teleoperation is subject to numerous constraints on time delay and accuracy. Nonetheless, results show that implementing this type of feedback in teleoperated robotic surgery results in a higher successes rate compared to the traditional robotic MIS. In this paper, we focus on improving the haptic feedback on the da Vinci robot at Aalborg University using the existing hardware. The method involves using a state-of-the-art haptic device to control a surgical tool serving as the robot's end-effector. Since the dynamics of the surgical tool are strongly non-linear, estimation techniques are used to calculate reaction forces on the device. Changes are made to the existing communication protocols in order to reduce time delay.**

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I. Introduction

Due to the advantages of robotic surgery, the interest in surgical robots has grown [1].
Increased precision provided by surgical robots introduces a decrease in tissue damage, thus reducing the recovery time [2]. Robots used in these surgical procedures have an attached end-effector that is used as a surgical tool. One such tool is the Endowrist. The main advantage of the Endowrist lies in its construction, as it is made to be manipulated in a similar manner to the operators wrist.

During surgery the operator receives feedback from the control loop. Commonly this feedback consists of visual cues in the video transmission of the surgery. The problem with the operator having exclusively visual feedback lies in the fact that the surgeon has to estimate the force applied by observing the deformation of the skin and organs for each maneuver. It has been shown experimentally that haptic feedback has a considerably positive effect on the reduction of surgical error [3].

The purpose of haptic feedback in Robotic MIS (RMIS) is to apply forces that resist the operator's movements to match the external forces applied to the end-effector. Haptic feedback gives the mechanosensory sensation of directly manipulating the end-effector, thus reducing the number of surgical errors.

The haptic feedback could be done as direct force feedback calculated from the resistance affecting the actuators, but as the tool is highly nonlinear, the transparency of the controller would suffer from it. It would be possible to solve this problem by implementing a sensor on the end-effector to measure the force, but due to the demand for high hygiene, the tools have to be sterilized at temperatures over a 100° C which could damage the sensor(s). Furthermore it is stated by law that each surgical tool has to be discarded after a few use. This means that the cost of the tool has to stay as low as possible and therefore make the idea of implementing an expensive sensor(s) not ideal.

Therefore the force feedback has to be estimated through the actuators, which gives a high performance demand for the feedback controller as it has to be as precise as possible to feedback the correct force to the operator. Another important subject is the transparency of the feedback, as the operator should have the feeling of doing the operation by hand and not remotely. This puts a demand on the speed of the feedback loop, as the faster the loop runs the smoother the force feedback to the operator will feel. This will set demands on communication frequency since we need to keep time delay to a minimum. It is widely discussed what the minimum refresh rate of the feedback loop should be but seems to be someplace between 300 Hz and 1000 Hz depending of the hardness of the object [4].

In section II, we will take an overview of our proposed control system as a whole, briefly presenting each of the components and their interaction. Section III will cover the methods used to create a dynamic model of the Endowrist and proposed methods of translating the estimated force to actual force fed back to the operator. Section IV contains descriptions of various problems pertaining the requirement of transparency and explanations of methods used to address them. Finally, we present (the expected) experimental results in section V and and draw a short conclusion in section VI.

II. System overview

A. Entire setup

A fully featured da Vinci robot with connected EndoWrists has four arms with 6 - 7 actuated DOF each. However, for test purposes, a small scale setup for controlling one EndoWrist has been created, see figure 1.

Representing the onboard computer on the da Vinci robot, an sbRIO board has been implemented to control the test setup. In

Fig. 1: Full view of the mechanical test setup

order to perform higher level functions, such as force feedback control, it is necessary to remotely handle data and send high-level commands. This is handled by an external computer system.

The sbRIO board communicates with the computer using User Datagram Protocol (UDP), while the Geomagic Touch, see section II-B, does so using TCP/IP. The computer performs force estimation using a dynamical model of the test setup (or EndoWrist, more precisely), this is vital for force feedback. In order to connect software components responsible for communicating with hardware and the ones responsible for the control algorithm and estimation, the Robot Operating System (ROS) is used. ROS uses a network architecture to share data between components via data streams.

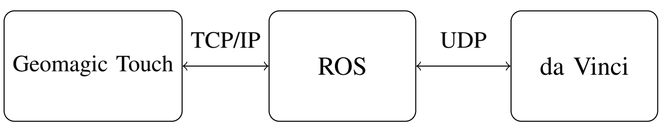


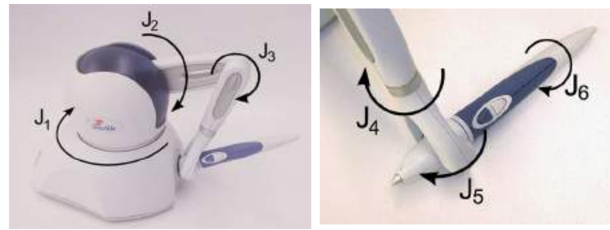
Fig. 2: Block diagram representing the system.

In our proposed system, the surgeon uses the Geomagic Touch joystick to control an EndoWrist tool on one of the arms of the da Vinci surgical robot. It is important for the operator to have a feeling of the resistance the tool is experiencing in order to adjust the position and grip strength and thus prevent damage to the patient's tissue. In order to project the reaction forces acting on the EndoWrist to the operator, we use the Geomagic Touch haptic feedback feature. The communication between the da Vinci robot, the Geomagic Touch and the controller is done through Robots Operating System (ROS).

B. Geomagic touch

The Geomagic Touch is a haptic feedback device, which has the ability to actuate its joints in such a way that the user feels resistance when moving the pen.

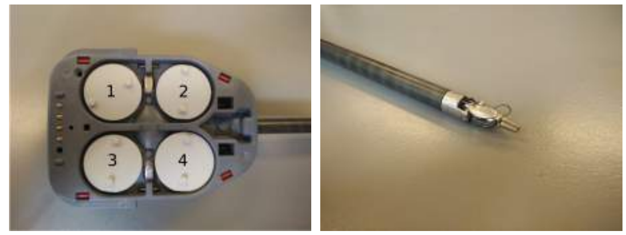
On Figure 3, it can be seen that the Geomagic Touch has six DOF, where the first three can be actuated, see Figure 3a. This means that the device has the ability to generate force feedback with three DOF, in this case roll, pitch and yaw.



(a) Overview of the Geomagic Touch's first three joints.

(b) Overview of the Geomagic Touch's last three joint

Fig. 3: Overview of all the Geomagic Touch's joints [5]



(a) Actuator plates, which can manipulate the end effector position

(b) End-effector of the EndoWrist

Fig. 4: The EndoWrist and its end-effector

C. EndoWrist

An EndoWrist, see Figure 4a is a surgical tool which can be manipulated as a human wrist. It is used in surgical procedures such as Laparoscopic surgeries, where small incisions in the human body is made during the surgery. Because the incision cuts are small, blood loss during the surgery and the risk of infection is reduced. This has a positive effect on the recovery time of the patient [2].

The EndoWrist can be manipulated as a human wrist with two clamps, thus having four degrees of freedom (DOF), see Figure 4b. This gives the movement of roll, pitch, yaw and an opening/closing mechanism that acts as the thumb and index finger of a hand.

The end-effector is manipulated by the four wheels seen on Figure 4a. The EndoWrist is cable driven, which provides the opportunity of making it small but also makes the system nonlinear due to dry friction.

III. Force estimation

In order to have a representation of the reaction force on the EndoWrist, estimation is needed. Because of the reasons mentioned in Section II, the force cannot be measured using sensors and thus have to rely on mathematical models as functions of torque measurements.

A. Mathematical model

The main challenge faced in making a model lies in the fact that the pulley system on the EndoWrist is nonlinear, and thus its full dynamics cannot be modeled in a straightforward manner. In other words, to have an accurate representation of Cartesian force a higher order model is required.

Another method of tackling this problem is to create multiple mathematical models pertaining to forces output by actions performed with the EndoWrist. In this manner, the feedback vector is transformed from Cartesian space to a task space in which the chosen actions form a basis. Each element of the new feedback vector corresponds to an actuated axis of the Geomagic Touch. For the purpose of this system, we choose the radial force generated by the yaw actuator, the tangential force generated by the roll actuator and the grip force generated by the clamps.

1) Grip force: The physical linear model for grip force can be derived [6]. A clear representation of grip force is important to the operator because it helps prevent excess grip application to soft tissue. This serves as a good starting point for a useable dynamical model.

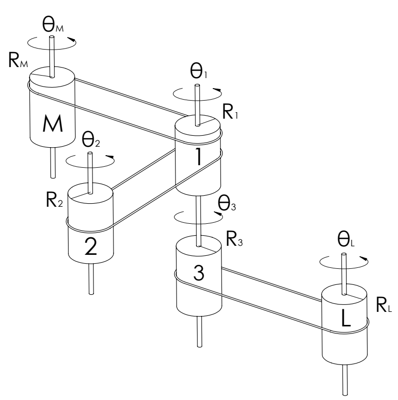


Fig. 5: The pulley system of the EndoWrist gripper modeled in [6].

The dynamical model in [6] is simplified to a 10th order state space system with 31 abstract, non-physical parameters, see equations 1-10. This is done to simplify the process of parameter estimation.

$$\dot{x}_1 = x_2 \tag{1}$$
$$\dot{x}_2 = A_1x_1 + A_2x_2 + A_3x_3 + A_5x_5 + A_7x_7 \tag{2}$$
$$\dot{x}_3 = x_4 \tag{3}$$
$$\dot{x}_4 = B_1x_1 + B_3x_3 + B_4x_4 + B_5x_5 + B_FF \tag{4}$$
$$\dot{x}_5 = x_6 \tag{5}$$
$$\dot{x}_6 = C_1x_1 + C_3x_3 + C_5x_5 + C_6x_6 + C_9x_9 \tag{6}$$
$$\dot{x}_7 = x_8 \tag{7}$$
$$\dot{x}_8 = K_mu_m + M_1x_1 + M_7x_7 + M_8x_8 \tag{8}$$
$$\dot{x}_9 = x_{10} \tag{9}$$
$$\dot{x}_{10} = K_Lu_L + L_5x_5 + L_9x_9 + L_{10}x_{10} \tag{10}$$

In equations (1-10), x_i represents the i-th state space vector element, while u_L and u_m represent the input signals for the pulley motors, see figure 5. The resulting state vector is described in (11).

$$\mathbf{x} = \begin{bmatrix}\theta_1 & \dot{\theta}_1 & \theta_2 & \dot{\theta}_2 & \theta_3 & \dot{\theta}_3 & \theta_m & \dot{\theta}_m & \theta_L & \dot{\theta}_L\end{bmatrix}^T \tag{11}$$

2) Radial and tangential force: Additionally, we can model the radial and tangential forces output by the yaw and roll mechanisms, respectively.

The tangential force is determined by the roll actuator and as such can be fitted to a linear model. This is done by simple measurement with the setup in figures 7a and 7b.

Linearity cannot be assumed for the radial output force of the yaw mechanism since it is also determined by the individual clamp actuators. In the case where only one action is performed at any moment, the model for this force again simplifies to a (piecewise) linear one. This assumption is confirmed experimentally as shown in figure 6.

B. Parameter identification

Parameter identification is performed using the Matlab parameter identification toolbox. To tune the model's parameters, it is necessary to perform experiments for input-output measurement datasets.

This is done by applying a known torque to the EndoWrist actuators and measuring the output force F, see figure 6. The goal here is to get a fully parameterized state space model which can be used for grip, radial and tangential force estimation with a Kalman filter.

At the time of writing this article, we are still in the process of developing a full setup for fitting models for grip and tangential forces.

On the other hand, the radial force model can be approximated linearly in a piecewise manner. This is done by using a linear approximation based on input torque and output radial force measurement.

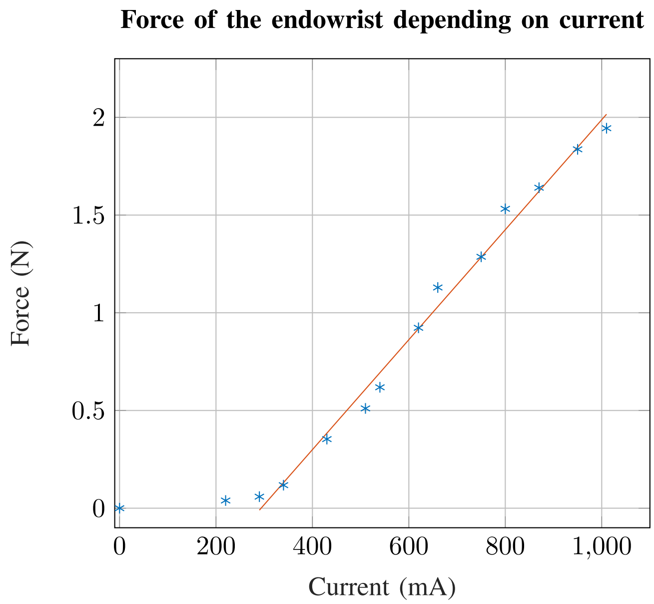


Fig. 6: The radial force measurements from the end-effector

(a) The entire test setup. From the right, a scale for measuring the radial force, a piece of wood for stiffening the EndoWrist and keeping it it place and the EndoWrist holder with motors.

(b) A 3D printed case which made it possible to make an orthogonal force from the end-effector to the scale.

Fig. 7: Test setup for the force estimation of the end-effector.

A piecewise linear expression is made from the 340 mA sample and up and can be seen on equation(12).

$$F = 0.0028\tau - 0.8259 \tag{12}$$

We consider the above equation appropriate for feedback loop implementation.

IV. Communication

The sbRIO board controls the motors for one Endowrist. The desired positions of the motors and the list of the enabled motors are sent to the board from the computer using an Ethernet cable. To perform force estimation, the computer needs to receive the list of the active motors as well as the position, velocity and effort for each of them.

It is said that the minimum refresh rate of haptic feedback is widely debated to be between 300 Hz and 600 Hz, but for a realistic force feedback it is commonly accepted to be at least 1000 Hz [4]. We decided to aim for 600Hz. In order for the system to fulfill this requirement it is necessary that the communication between the sbRIO board and the computer at least match this frequency.

In order to get the fastest communication it was decided to use UDP as it does not implement any reliability feature. Network reliability is undesired in our communication system as it would just lead to retransmitting obsolete data instead of transmitting new one. Furthermore, most of the transport protocol implements features that improve long distance communication which would be superfluous, as the computer is directly connected to the robot.

In addition to the transport protocol, another factor that influence the speed of the communication is the size of the sent packets. To maximize the speed of the communication, the size of the packets must be minimized while keeping the computation time as low as possible. As stated before, the packets exchanged between the computer and the sbRIO contain numerical values (positions, velocities and efforts) and booleans (active or enabled motors). The bitcode of the numerical values is interpreted as ASCII characters and the booleans are gathered in one byte which is also interpreted as a character. Those characters constitute the payload of the packets. As each numerical value is stored on 4 bytes, in the test setup which has 4 motors, the size of the payload sent by the computer to the sbRIO is 17 bytes and the size of the payload sent by the sbRIO to the computer is 49 bytes.

To investigate the quality of the communication as a function of frequency three parameters are measured: the round-time trip delay, the jitter and the error rate. However, as the software does not have a way of directly setting the frequency of the communication it is the delay in the communication loop that is modified through the experiment. The computation time and transmission time of the packets being non negligible, the frequency of the communication is not equal to the inverse of this delay.

V. Results

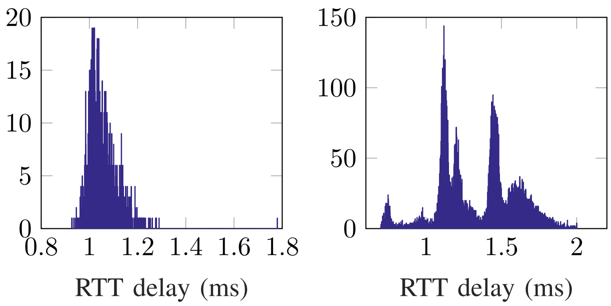
A. Communication

It was stated before that the requirements for our system was to get to at least 600Hz and to reach 1000Hz if possible. As shown in Table I, the connection can go up to almost 1000Hz using UDP which fulfills the requirements. However, the jitter should not be neglected as the frequency get closer to 1000Hz the jitter increases and becomes high compared to the period and may cause unexpected behavior in real time operation. It is though that as the period become smaller, the system becomes more sensitive to the preemption of other processes.

Delay	Frequency (Hz)	RTT* delay (ms)	Jitter	Error rate (%)
10ms	86	1.1	4.9E-8	0
0ms	981	1.3	6.1E-8	5.1E-5

*Round Time Trip
**The number of data set needs to be increased for the final version

TABLE I: UDP**



(a) delay = 10ms

(b) delay = 0ms

Fig. 8: distribution of the RTT delay for different parameters

VI. Discussion

Due to the structure of the Endowrist, we have split the dynamical model of the force into separate submodels pertaining to the actions most commonly performed. A model was defined both for the grip, radial and tangential forces of the clamping tool.

The grip and tangential force models parameters are still to be defined through experiments performed using a load cell for grip force measurement. Based on earlier results [6] we expect an approximation of grip force adequate for feedback.

For the radial force, the linear model parameters are defined and we expect the model to be precise in action since it fits the experimental results well. Additionally, it is simple to calculate so it doesn't introduce noticable delays in the system.

For usable information to be provided , the representations of feedback from these three models need to be mutually independent. This means that the feedback force vector representing the e.g. yaw mechanism on the Geomagic Touch needs to be linearly independent of the ones resulting from the other two mechanisms. We can easily do this by pairing individual actions with horizontal and vertical movement of the Geomagic Touch end effector, as well as the rotation of it's first joint .

In the communication between the sbRIO and the computer, it was decided to not compress transmitted data as the size of the packets is small (maximum of 49 bytes of payload). The compression rate for this amount of data is usually small and the computation time induced by compression and decompression lead to either a very small reduction of delay or even an additional delay. However no detailed study was made in this project to investigate the exact compression rate and computation time that would result from compression.

By chosing UDP as a transport protocol, every network reliability feature was removed from the connection which match the demands of our system in term of bandwidth. However, safety needs to be considered for such a system. As such a feature was implemented on both side of the communication in order to detect packet loss and connection timeout. The detection of those event allows to stop moving the end-effector and to notify the operator. In the future, additional steps such as protection against external attacks and handling of packet losses should be taken in order to improve the overall safety of the system.

VII. Conclusion

A new communication protocol implementing UDP and transmitting bitcode has been designed to exchange data between the sbRIO and the computer running ROS. It was shown through experiments that the new protocol provides an improved bandwidth without implementing new hardware.

An action-based approach to output force modeling has been taken. We believe that this way force information is resented to the operator in a more useful manner than direct Cartesian force feedback. Additionally, this approach simplifies calculation and avoids adding significant delays to the system.

References

[1] Trefis, "Intuitive surgical expects q4 growth on rising da vinci xi sales," http://www.forbes.com/sites/greatspeculations/2015/01/15/intuitive-surgical-expects-q4-growth-on-rising-da-vinci-xi-sales/#433ce1a26d7c, accessed: 24-11-2016.

[2] P. C. Giulianotti, A. Coratti, M. Angelini, F. Sbrana, S. Cecconi, T. Balestracci, and G. Caravaglios, "Robotics in general surgery: personal experience in a large community hospital," *Archives of surgery*, vol. 138, no. 7, pp. 777–784, 2003.

[3] J. C. Gwilliam, M. Mahvash, B. Vagvolgyi, A. Vacharat, D. D. Yuh, and A. M. Okamura, "Effects of haptic and graphical force feedback on teleoperated palpation," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on.* IEEE, 2009, pp. 677–682.

[4] T. R. Coles, D. Meglan, and N. W. John, "The role of haptics in medical training simulators: a survey of the state of the art," *IEEE Transactions on Haptics*, vol. 4, no. 1, pp. 51–66, 2011.

[5] Sigverse, "Using phantom omni haptik device," http://www.sigverse.org/wiki/en/index.php?Using%20Phantom%20Omni%20Haptik%20Device, 2014, downloadet: 21-10-2016.

[6] C. Y. Kim, M. C. Lee, R. B. Wicker, and S.-M. Yoon, "Dynamic modeling of coupled tendon-driven system for surgical robot instrument," *International Journal of Precision Engineering and Manufacturing*, vol. 15, no. 10, pp. 2077–2084, 2014.