Modelling and Control Framework for Robotic Telesurgery

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***Abstract*—Frequently encountered limitations of hardware and software systems regarding teleoperation capabilities include the incomplete modelling of robot dynamics, tool–tissue interaction, human–machine interfaces and the communication channel. Furthermore, the inherent latency of long-distance signal transmission may endanger the stability of a robot controller. All of these factors contribute to the very limited deployment of robotic telesurgery. This paper gives an overview of the challenges of establishing high fidelity telepresence systems for medical applications, and proposes development directions beyond the state of the art.**

Keywords—telesurgery; robot control system; latency

I. Introduction

Long-distance surgical procedures supported, or performed by robots would open up new frontiers in medical interventions. This was the initial idea behind the first concepts when they appeared at NASA in the early 1970s [1].While the concept of telesurgery in space never reached beyond simulations, by 2001, it was possible for the first time to perform surgery on the basis of ISBN-based intercontinental communication [2]. This proved that in urgent cases—in theory—doctors could reach out to patients hundreds or thousands of kilometres away. The interventions could be executed in places difficult to reach (remote rural areas) or dangerous for people (war zone). DARPA (the US Department of Defense) has sponsored various projects—most notably the TRAUMA POD—to develop a technology that supports injured soldiers on the battlefield without risking the Medical Doctor's life [3]. Nevertheless, the difference in the complexity between supporting a distant operation on Earth and one in space is huge. Human space exploration is unimaginable without full medical support (despite the recent announcements of plans from a Dutch consortium to initiate a one-way Mars mission [4]), yet it is impossible to send an entire medical crew with the spacecraft because of the high costs and the limited space. This severe constraint keeps the research open towards telesurgical solutions, since many of the possibly emerging problems could be solved with one surgical robot sent along the expedition. Thus, proper modelling and control of both master and slave side remains an important research topic [2]. Communication with the surgical crew on Earth creates further tasks to solve. Most of the problems are caused by signal latency, which get worse with the increase of the range of the mission. Some of the disturbing effects of a generally proposed teleoperational surgical robotic system can be reduced by well-chosen system architecture and control. Current options are investigated in this paper.

II. State of the Art

The best known surgical robot is the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA), functioning as a teleoperated manipulator. Over 2,800 da Vincis have been sold around the world to more than 2,000 hospitals [5]. Although the system is not used routinely for distant telesurgery as the master and the slave are just a few metres away from each other (due to the limitation of the custom-developed communication protocol), the potential has been there to make it work at a greater distance, and some limited experiments have been performed. DARPA presented collaborative telerobotic surgery with modified da Vinci consoles in 2005, being able to overtake the controller with another through the Internet [6]. The Canadian Surgical Technologies and Advanced Robotics (CSTAR, London, ON) used the core network of Bell Canada to test the telesurgery-enabled version of the da Vinci. Six successful telesurgical porcine pyeloplasty procedures were performed in Halifax, Nova Scotia—1,700 km away from London, ON[7].

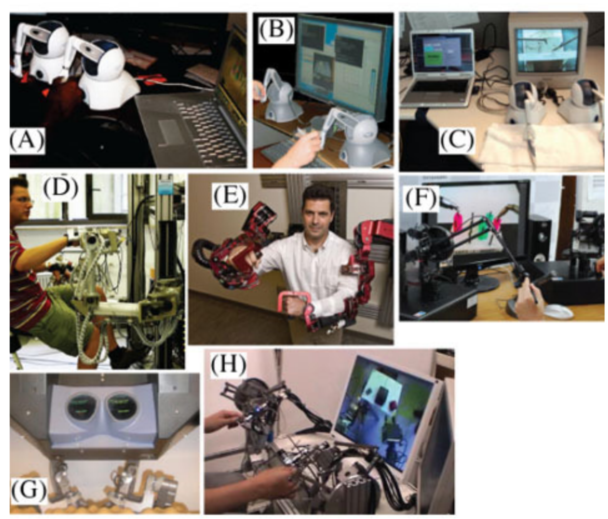

Fig. 1. Interconnected master devices of the 2009 world wide Plugfest event, demonstrating the capabilities of current telesurgical architectures [8].

An outstanding experiment of the domain was the Plugfest in 2009 (Fig. 1), when eight master devices were interconnected with six slave machines [8]. The custom-developed communication *Interoperable Teleoperation Protocol* (ITP)has been successfully used over 24 hours, supporting efficiently the simulated interventions (peg transfer task of the SAGES Fundamentals of Laparoscopic Surgery [9]). The reliability of the public Internet network has recently advanced to a stage where these experiments could safely be arranged. In the meanwhile, the newest data show that the Internet backbone infrastructure is getting overloaded, therefore the lags are increasing [10]. The security of the system should be developed in the future for the protection of the patients (in accordance with IEC 80001-1:2010). Nevertheless, surgeons will have to get prepared for the u

se of these robots through special training courses, since the disturbing effect of latency also has to be learnt to tolerate and be compensated by the operator as much as possible.

III. TELEOPERATION SYSTEM COMPONENTS

Just as in the case of other teleoperational systems, surgical robots also have three major components from the modelling and control point of view: master device, slave device and the communication system. On the top of that, the tool–tissue interaction should also be assessed. The modelling of these components is indispensable in order to build a valid simulator for the whole system to observe and analyze certain control attributes and behaviours. These models should be validated independently first, and the modelling error should be examined in each case.

A. *Communication system*

The communication system includes the transmitter, the receiver and the communication medium. These, in total are responsible for the quality of the signals and the latency. The package loss is a generic phenomenon that is better handled by some protocols, such as the *User Datagram Protocol* (UDP) [11].

The communication delay must be kept at a low level, because human can only adapt to a limited amount of time delay, typically max 0.5 s. The first trans-Atlantic telesurgery was built on the *Zeus* robot (Computer Motion, Mountain View, CA) in 2001, where the mean signal delay was 155ms, which is easily adaptable by humans [12]. It was a 85ms lag in signal transmission, while the remaining 70 ms was the encoding and decoding time for the video. Depending on the level of latency, we can talk about three types of technologies:

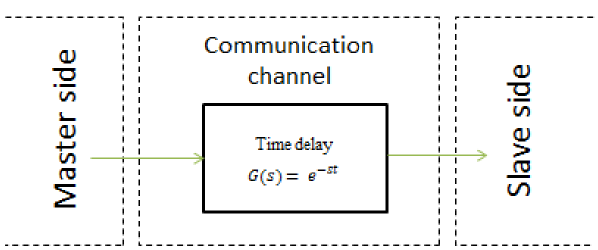

Fig. 2. Block diagram of the time delay model employed in telesurgery robot control.

- Telesurgery (max. 2s)
- Telementoring (max. 50–70s)
- Teleconsultancy (max. 15min)

The effect of time delay could be reduced with latency-tolerant control methods, thus larger distances can be bridged by these systems [12]. To achieve this, robust models of the system components are required. The complete architecture is proposed to be approximated with three models. The master includes the controller and the human operator, which is connected via a high-delay medium to the slave model that covers the intervening master arm. In the deriving cascade setup, the time delay can be partially alleviated using appropriate predictive controllers tuned to the master and slave systems [13].

The simplest possible way to model a T time delay element is described by the following formula [14]:

$$y(t) = u(t - T). \tag{1}$$

For the sake of simplicity, let the input be $u(t) = e^{st}$.Then, the output is given by the following formula:

$$y(t) = y_0 e^{st}. \tag{2}$$

Thus, (1) can be written as follows:

$$\begin{aligned} y(t) = y_0 s^{st} &= e^{s(t-T)} = e^{-sT} \cdot e^{st} \\ &= e^{-sT} u(t) \end{aligned} \quad . \tag{3}$$

The signal delay can be modelled by the $G(s) = e^{-st}$ transfer function, as it has been illustrated in Fig. 2.

B. *Master model*

The master side is where the "*human operator*" or the replacing automatic control device is located. Further, the surgical staff can be found here, providing the control signals for the actuators of the slave. A commonly used human model is the *crossover model* that was developed in the 1960s for fighter pilots 0. It is based on the highly non-linear and time-dependent response of the human body, but it is well-approximated by a quasi-linear model. The model complexity depends on the precision that the execution of the task requires, but the following form provides a reasonably good approximation:

$$H(s) = K_p \cdot \frac{\tau_L s+1}{\tau_I s+1} \cdot \left(\frac{e^{-\tau s}}{\tau_N s+1}\right), \tag{4}$$

where the bracketed term refers to the human physiological limitations. Accordingly, the term$e^{-\tau s}$refers to the signal

delay that occurs during human reaction. The term $\frac{1}{\tau_N s+1}$ represents the neuromuscular system delay. K_p is the static gain of the operator, $\frac{1}{\tau_I s+1}$ is the time delay section and the term $\tau_L s+1$ is the control time constant. The model is not extended to all the details of human attributes, such as the subject's motivation, expertise, but the effect of delay can be measured with it. Further, the distorting effects of tiredness, stress needs to be formulated within, adding the effect of time delay on the top. The human operator model proposed is shown in Fig. 3.

Another human operator model was introduced by Ornstein, which is slightly more complex, and it is also applicable for pursuit-type manual tracking tasks [15]:

$$H(s) = \frac{a_1 \cdot s + a_0}{b_2 \cdot s^2 + b_1 \cdot s + b_0} \cdot e^{-s\tau}, \qquad (5)$$

where a_1 arises from the velocity component and τ is the transport delay. The determination of the values of the coefficients was discussed in [15].

The number of parameters represented in the model can make it more sophisticated, allowing one to obtain a more accurate description of basic human behaviour. The neuromuscular limitations can be well-described by certain time delay elements and different dynamic response characteristics [17], while human sensing can be characterized by threshold elements. A variety of sensory input noise is modelled as a member of general signal noise, which can also be used in the modelling of vision. Introducing non-linearity will have similar effect, increasing the complexity.

One of the most applicable non-linear car driver models is the GM/UMTRI model, developed for General Motors. This is an extension of an older quasi-linear UMTRI driver model [18]. The block diagram of the model is shown in Fig.4. These models have been shown to represent the master–slave type telesurgery tasks [19].

IV. Slave Model

While not all of the latencies can be avoided, empowering the salve system with autonomous capabilities can also improve functionality and safety. Robust control methods may further reduce the effect of latency. Thus, better and more appropriate control for the presented tasks needs to be investigated. The slave robot's kinematic model is typically given to a fine level of details, enabling its integration into kinematic and dynamic models [20], [21].

It is most challenging to gain information about the interactions of the robot arm and the tissue. It is possible to gain this information if force feedback is provided, but among

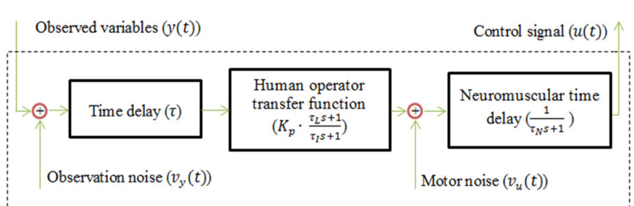

Fig.3. Multivariable, yet one value driven model of a human, operating as a controller.

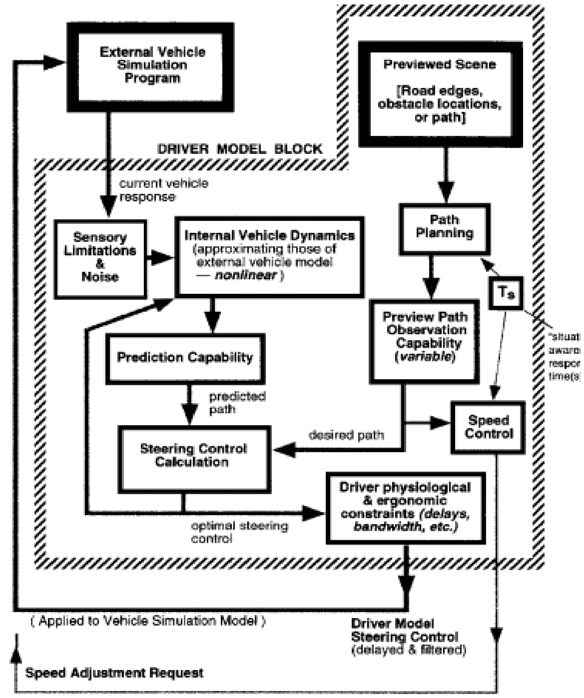

Fig.4. The GM/UMTRI non-linear car driver model, shown to be applicable to robotics surgery [18].

today's surgical robots, this option is not common [22]. Static models may be used instead of the dynamic models, since the effects on tissues are relatively small, due to the fact that current trends are focusing on minimal invasiveness.

Table I. summarizes the most important models used for tool–tissue interaction in surgical robotics, enlisting some of their basic properties. Depending on the surgical device and the complexity of the anatomy, different models are to be chosen.

When choosing a controller for the entire system, all the model parameters should be considered, and in order to increase the robustness, the overall complexity and rank of the models should be kept as low as reasonably possible [13].

V. Discussion

Rapidly developing robotics technology and communication infrastructure boosts telesurgical applications. However, these concepts still need the right choice of models, considering accuracy, robustness and computational requirement. Separate models must be used for the master controller, the robotic arm, operating tool and the tissue itself, whereas the time delay and the lack of adequate feedback greatly affect the controller's performance. As described in this paper, it is typically possible to perform a task based on a simplified, or complex, non-linear models as well, but the increasing complexity and lower performance of the employed control system may not worth it after all.

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Table I List and basic properties of the most commonly employed soft tissue models for robotic surgery applications.

Model number	Used for	Tissue model	Tool model	Feedback type	Sensors	Model complexity	Reference
1	Analyzing transparency under slave link and joint flexibility	Rigid	Linear elastic	Force feedback to user's hand	Position and velocity sensors at tool tip	Varying, from simple to moderate. Determined by the mechanical model of the tool.	Tavakoli*et al.* 2009 [25]
2	Medical training through simulation in virtual reality	Mesh based FEA model, using modal analysis	rigid	Force and torque feedback to user's hand, collision detection and detection of multiple tissue layers	Force and position sensors mounted on the tool, held by the user	The complexity is determined by the level of system reduction	Basdogan *et al.* 2004 [26]
		Real-time method of finite spheres				Simple, with minimized computational effort	
3	Detecting lumps in organ tissues (kidney, liver, heart)	7 different models, model validation on real tissues	rigid	No feedback to human user	1DoF force feedback from point-to-point palpation	Increased accuracy with model complexity	Yamamoto 2011 [27]
4	Detection of lumps in prostate tissues, definition of forbidden regions for patient-side manipulators	Manufactured artificial tissue based on existing commercially available artificial prostate	rigid	3D visual feedback generated with a stereo-vision system	Position, velocity and force sensors on slave manipulator	Hunt-Crossley, a complex but accurate model	Yamamoto *et al.* 2012 [28]

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