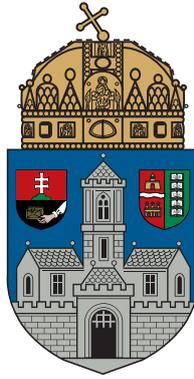


# Óbuda University

PhD Thesis Summary



## **Soft Tissue Models for Enhancing Force Feedback in Teleoperation Systems**

**Lágyszövetmodellekkel támogatott erővisszacsatolt  
teleoperációs rendszerek**

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Budapest, 2017

## Scope of Research

In the past 20 years, research activities related to robotic surgery have gained much attention due to the rapid development of interventional systems. Advanced surgical devices present a fine example of Human–Machine Interfaces as well. While many surgical maneuvers have already been implemented with a degree of autonomy, most of these surgical robotic devices are still used as teleoperation systems. This means that a human surgeon is always required to be present in the control loop, as an operator. Parallel to the evolution of telesurgery, different model-based control methods have been developed, and experimentally tested. These enhance transparency and increase latency-tolerance, both in terms of long distance (space robotics, intercontinental operations) and short distance (local on-Earth scenarios) teleoperation. The effectiveness of traditional real-time control methods decreases significantly with the increase of time-delay, while time-varying latency introduces further challenges. A suitable controller can ensure high quality control signals and improved human sensory feedback. This can only be achieved by adequate models for all components of the telesurgical systems, including models of the human operator, the robot and the tool–tissue interaction. Using haptic controllers and accounting for the tissue dynamics, one can also address issues arising from communication latency. Stability and accuracy deterioration caused by latency and other external disturbances, such as contacting hard tissues or elastic tool deformation, can also be accounted for by using realistic soft tissue models. The integration of these models into model-based force control algorithms largely increase the robustness and reliability of robot-assisted interventions.

In telesurgery, cutting, indentation and grasping are just a few types of tissue manipulations that require high precision tools and techniques. The majority of modern telesurgical systems use only visual feedback, while the applicability of force or haptic feedback has been a lasting research topic in the field. An efficient implementation of force control incorporating haptic feedback can enhance the surgeon’s sensory capabilities during the operation. In order to achieve better performance for surgical robotics applications—in terms of stable control for teleoperation—it is crucial to understand the behavior of soft tissues through modeling their mechanical properties.

Creating an accurate tool–tissue interaction model would largely aid the design of model-based control methods. This way, force response of the manipulation is estimated using the model, and the required input force (control signal) can be derived. This allows the control of the tissue manipulator (in most cases, a surgical tool held by the robotic arm), in order to carry out the surgical manipulation tasks in an efficient, stable and accurate way.

The problem of distinguishing between soft tissues by testing their mechanical properties is often referred to as the cognitive role of haptic devices in simulation

environments. It is a common view that today's surgical simulators that are using haptic interfaces should rely on simple mechanical models of soft tissues, instead of complex, parameterized finite element models, thus enhancing real-time operation and focusing on the most representative mechanical effects, such as creep (the phenomenon of permanent deformation due to mechanical stress), stress relaxation or residual stress.

This work presents a novel method for enhancing force feedback in teleoperation systems using a model-based approach. The aim is to address the design challenges of master-slave type telesurgical systems, which mostly arise from the system complexity, the communication delay and the integration of haptic feedback between the master and slave devices. This way, the most relevant qualitative and quantitative indicators of robotic systems can be improved, such as precision, performance and reliability. In order to achieve the control goals, modeling of the tool-tissue interaction during the procedures is crucial, which requires the formulation and verification of a generalized mechanical soft tissue model. This can be used for reliable reaction force estimation during a pre-defined surgical intervention.

Given an appropriate soft tissue model, its integration is possible into a user-defined model-based control method, which allows its direct implementation into modern surgical robotics systems. This work also gives a theoretical background on the methodology and verification of a proposed nonlinear soft tissue model. The verification is supported by a practical methodology on the integration into the da Vinci Surgical System, and the corresponding development environment, the da Vinci Research Kit. A polytopic model-based interaction controller is proposed, and control performance is investigated in order to address robustness against model uncertainties and time-delay.

Along with force control, the problem of haptic feedback in telesurgical systems is also addressed in this work. The da Vinci Surgical System currently lacks haptic feedback capabilities, limiting its usability in everyday surgical practice. This thesis proposes a validation method for tissue models and their polytopic representation by creating an experimental framework using the da Vinci Research Kit. Once allowing haptic feedback from the manipulated real tissue, this feature can be extended to surgical simulation using virtual tissue models, based on the proposed soft tissue modeling method.

The field of application of the proposed methods can be divided into three large groups. First, robotic surgical systems with haptic feedback capabilities can be improved by reflecting an estimated reaction force to the operator, based on the tissue mechanical properties and deformation data. Second, surgical simulators for training and education can be enhanced by implementing the tissue model, creating a realistic virtual environment for practical training and trials on specific interventions, such as prostatectomy, cholecystectomy or appendectomy. Third,

the proposed model-based force control method can improve the performance of automated tissue manipulation tasks for fully or semi-automated surgical systems, including suturing, coagulation, cutting and grasping.

The integration of the proposed methods and models into clinical use is a question of availability of hardware and software components, too. The commercially available telesurgical systems were dominantly not designed to reflect force feedback to the operator, therefore a new stable slave component is needed for reliable operation. Such systems are under development, but these are still awaiting commercialization and approval from national and global regulatory bodies. In the meanwhile, there is a wide range of components available for research and development uses, both in terms of hardware and software. Open-source repositories and global communities are actively working on the enhancement of prototypes and commercially available surgical systems, where methods and models, such as the ones presented in this work can be further developed, tested and validated.

## **Research Problem Statement**

Robots are gradually entering the operating room, aiding, or completely taking over different surgical maneuvers. The state-of-the-art is that these robotic systems are used as human-operated, telesurgical systems, where the human operator is an integral part of the control loop, while the robot is mimicking the gestures of the surgeon. The primary aim of telesurgical devices is to enhance the performance of the surgeon, applying hand tremor filtering, virtual guiding and motion scaling. From the engineering point of view, these teleoperation systems should provide a transparent, reliable and robust operation, which requires advanced approaches in terms of controller design and system modeling. In order to avoid stability loss and accuracy deterioration, the problems of signal latency due to the remote operation, elastic tool deformation and undesired hard tissue contact can be addressed by reliable soft tissue models. This way, various scenarios of the tool–tissue interaction can be approached from the modeling point of view.

Robot-assisted tissue manipulation requires high precision tools and techniques. Today's telesurgical systems dominantly rely on visual feedback, the commercially available systems do not provide haptic feedback to the surgeon. As the placement of force sensors into the surgical tools used in Minimally Invasive Surgery is very challenging, an alternative approach is needed for indirect reaction force estimation, in order to provide force sensation to the operator. Furthermore, automated surgical interventions also require an estimation of the behavior of the manipulated environment. The unique behavior of soft tissues as viscoelastic materials can only be described by sophisticated mathematical models, as the currently used models are only representing the predicted behavior locally. As the

soft tissue is an integral part of the manipulation, the integration of its model at various level of engineering design is crucial.

- *Problem 1:* There is a need for a general soft tissue model that can represent soft tissue behavior during surgical interventions. The model should give a relation between tissue deformation and the reaction force, and should give a quantitative representation of the material, with adequate spatial and temporal resolution.

Teleoperation systems in general require sophisticated control approaches in order to assure transparency of the system and increase reliability. Modern telesurgical systems dominantly use traditional control approaches in order to increase robustness, which often means a trade-off for the accuracy requirements. An appropriate tool–tissue interaction model opens up the possibility for applying model-based control methods, allowing a direct implementation to complete surgical robotics systems. Modern model-based controller design methods are limited by the mathematical representation of the system, therefore bringing the interaction models to a design-compatible form is essential.

- *Problem 2:* Control methods in telesurgical applications need to rely on sophisticated models of the tool–tissue interaction, requiring the models to be represented in predefined forms. In the meantime, the controller performance should be robust against time-delay and modeling uncertainties.

Haptic feedback in robot-assisted surgical systems offers the possibility to reflect the estimated or directly measured reaction force to the operator. Furthermore, surgical simulators with haptic feedback can introduce an important function for surgical training in education, where accurate soft tissue models can be used for creating virtual surgical scenarios. As different haptic devices provide different sensation and scaling of the reflected force, there is a need for a performance evaluation of the Human–Machine Interface for specific setups, addressing the validity of the utilized soft tissue models.

- *Problem 3:* A general methodology is needed for addressing the usability and validity range of tool–tissue interaction models in telesurgical scenarios, where haptic feedback is available. The methodology should be extended to both living and artificial tissues, and an appropriate framework is required for data acquisition, processing and evaluation.

Modeling of telesurgical systems is a complex task, where tool–tissue interaction and soft tissue modeling play an essential part. However, the appropriate models of the slave side (robotic arm), operator behavior and the communication

system all have to improved simultaneously in order to achieve a superior performance in telesurgery. The problems stated in this chapter are focusing on an important part of model-based design and usability approaches, their discussion in this work proposes solutions that can aid the further research of the scientific community in the field.

## **Materials and Methods**

During my doctoral research, I relied on specific methods in terms of experimental data collection, research protocols and techniques. Each of the research problems and statements of the hypotheses were relying on these methods. This chapter provides a detailed description of the research plan, step-by-step, focusing on its elaboration in the thesis groups.

The primary question in my research proposal was related to the state-of-the-art of the existing tool–tissue interaction models. It was my goal to investigate, to what extent this models could be used for improving the performance of telesurgical interventions, with special attention to the model description, its integrability into control methods in general, and finally, the validity of the specific interaction models in the wide range of telesurgical applications.

As of today, there is no general consensus on which tool–tissue interaction to chose for specific applications. An ambitious plan was formed to propose a general model that can be utilized in a wide range of intervention modeling, which required the investigation of the current tool–tissue interaction models, analyze them and find the best-fitting high level approach for my goals. I have created a structured list for my literature research, where I collected the properties of the investigated tool–tissue interaction models, available from the most extensive scientific paper libraries in the topic. I have collected the modeling approaches used in these works, focusing on soft tissue models, tool models, clinical use case, feedback type to the operator, applied sensors and model complexity. The literature research was covering the material of over 50 scientific papers in the topic of tool–tissue interaction, distinguished by their number of citation, publication date and relevance. Novel, well-cited papers with explicit focus on tool–tissue interaction received a higher preference, while older, less-cited ones were used as a reference in the comparison and assessment of modeling approaches.

After concluding the first phase of the literature research, I have collected 3 tool–tissue interaction models, which provided promising approaches for the improvement of telesurgical performance, tackling 3 independent challenges in modern surgical robotics design: the flexibility of cable-driven surgical tools; the problem of motion compensation in the case of moving organs; and the mechanical modeling of soft tissue behavior during the tool–tissue interaction. While

there is a rich literature discussing methods for dealing with these challenges, I have decided to conduct a deeper investigation in the field of soft tissue modeling, proposing that a sufficiently accurate soft tissue model can be generalized for a wide range of modeling surgical interventions. Such model could be directly utilized by various tool–tissue interaction approaches, e.g., modeling cable-driven interaction.

The behavior of soft tissues and viscoelastic materials have been the subject of research for long, not restricted for surgical robotics applications. However, a general soft tissue model has not been proposed yet, most of the approaches can be sorted into three large groups:

- rheological models,
- continuum-mechanics based models,
- hybrid models.

In search for a general solution, which could quantitatively represent the macroscopic mechanical properties of soft tissues, my literature research was focusing on rheological models and their use for specific tissue modeling and characterization applications. Based on the collection of research papers utilizing this approach, I created an overview of the existing model variations, addressing their advantages and disadvantages, finding that the Wiechert model provides the most general, yet simple description of tissue behavior.

As there is no generally accepted verification method for addressing the validity of soft tissue models, my aim was to propose a methodology that can aid the quantitative comparison of different viscoelastic materials using the Wiechert model. This part of the work was done in two phases. First, existing measurement data from the available literature was used for verifying the model. Second, experimental data was collected in a structured way, proposing a methodology to create a diverse set of measurement data. In these sets of measurements, reaction force data from tissue compression was recorded under known deformation profiles, and the soft tissue model verification was carried out by fitting the simulated tissue behavior on the measurement data, finding the best fitting set of mechanical parameters representing the Wiechert model. The curve fitting was utilizing the widely-used Root Mean Square Error (RMSE) minimization of the distance of measured and simulated data points. This method was later used in the same sparsity of data points for the performance evaluation of the model for different scenarios.

Taking the Wiechert model as a basic example, investigating the measurement data from the compression tests, I used an analytical method for improving the performance of the linear model. This included a proposal of introducing different types of nonlinearities into the structure, conducting further research on the

limited literature available on nonlinear rheological models. Based on practical consideration, I have introduced the nonlinearities through the spring elements of the Wiechert model, and obtained the parameters of the investigated tissue models using curve fitting methods described. The model verification for uniform and non-uniform surface deformation was following this methodology as well.

The experimental data collection was carried out based on a carefully assembled measurement plan, and was documented for better reproducibility. The measurements required a palpation tool that was capable of maintaining a prescribed compression rate and recording the reaction force by the compressed tissue either by an in-built or mounted force transducer. The simultaneous recording of displacement and force allowed me to create a structured set of data for evaluation. This data collection method was used both for *ex vivo* and artificial tissue samples, where the samples were cut or molded to a prescribed geometry and dimensions. This way, the method can be standardized, and the quantitative comparison of the tissue parameters can be validated.

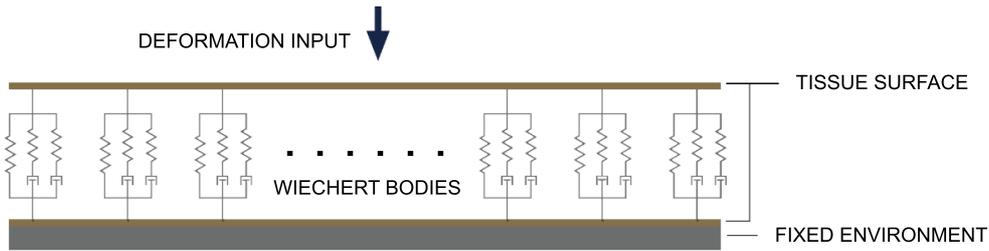


Fig. 1. The proposed tool–tissue interaction model, where the Wiechert elements are distributed along the tissue surface. I showed that in the mass–spring–damper soft tissue modeling approach, linear models do not represent the relevant soft tissue behavior characteristics simultaneously, therefore I proposed and verified a nonlinear Wiechert model.

Having verified the tissue model, I have conducted an extensive research on model-based control methods in robotic surgery, where soft tissue models were utilized to some extent. By investigating these approaches, I found that very few of them were relying on complex, nonlinear tissue models, requiring a controller design for linear or quasi-linear model representations. In order to achieve robustness and to design a controller system that is stable in the Lyapunov sense, LQ optimal control is a popular approach, where the controller is in the form of a Parallel Distributed Compensator (PDC). The method required a discretized representation of the nonlinear system and a control architecture. Polytopic Tensor Product (TP) modeling in an emerging field in the representation of nonlinear systems for such control problems. Based on this consideration, I created the Minimal Volume Simplex (MVS) polytopic TP form of the proposed nonlinear Wiechert model, and verified it by investigating its behavior on predefined deformation in-

put functions, comparing the output to the one of the qLPV representation of the system.

The verification of the TP model was followed by the proposal of different control architectures, which were tested in the MATLAB Simulink (MathWorks, Inc, Natick, MA) simulation environment. As the conventional control architectures failed to solve the control problem in practice, I proposed a new modeling methodology in order to comply to the requirements of the controller design. The model was tested and verified on simulated tracking tasks, and was tested against robustness in the simulation environment as well.

The polytopic representation of the model allows its easy integration into the da Vinci surgical system, which was the first step towards proposing a tissue characterization methodology. Such representation allows one to use a large variety of control schemes for force control applications, allowing the reformulation of the highly nonlinear system to the interpolation of linear dynamic systems. The aim of this phase was to address the usability and validity range of the proposed soft tissue models, integrating it to a force-feedback palpation scenario, tested by a representative group of participants. The planning of the tissue characterization experiments were based on the findings of the literature research on trials with haptic devices, investigating different approaches to palpation scenarios, the average number and professional background of participants. The characterization trials were using the da Vinci Surgical System as the haptic interface, utilizing the da Vinci Research Kit (DVRK) and the Robot Operating System (ROS) platform. The palpation scenario was based on the guidelines from the automated tissue palpation experiments, but the compression rate was controlled by the participants during the trials. The participants were asked to carry out simultaneous

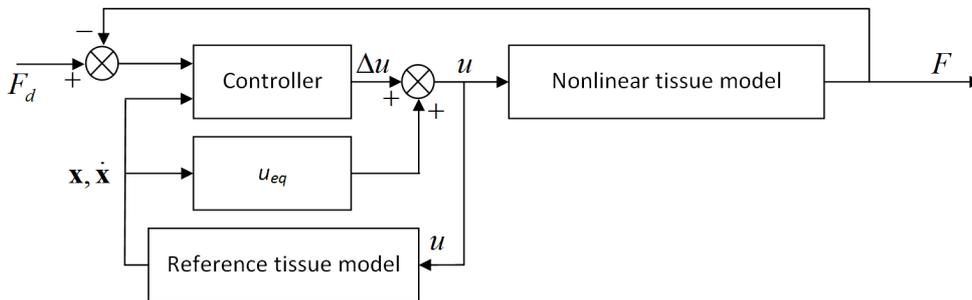


Fig. 2. Schematic block diagram of the proposed control scheme. Due to the slow poles of the system, the conventional design strategies are not applicable, therefore I proposed a new control scheme for the polytopic representation of the tool–tissue interaction model and verified the controller for robustness in terms of parameter uncertainty and time delay.

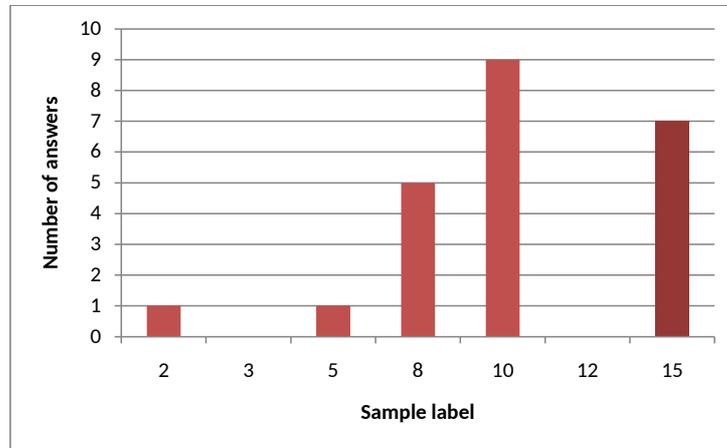


Fig. 3. Tissue characterization results, summarizing the participants answers to the question: 'Which virtual tissue model's behavior resembles the most to the *ex vivo* chicken breast?' The correct answer is indicated by a different color, belonging to sample 15. The results verify the realistic behavior representation of the nonlinear soft tissue model and validate the use of artificial soft tissue samples in education and research.

palpation using both of the master tool manipulator arms of the da Vinci master console, controlling the palpation tool with their left hand, and palpating a virtual, polytopic representation of different tissue models. Then, they compared the real and virtual tissues, and looked for the match of the *ex vivo* sample from the different virtual ones. Their comments and final guesses on the matching tissue were recorded and evaluated both verbally and quantitatively. The collected data from the automatic tissue palpation for parameter estimation, and the characterization trials provide structured, aggregated data for further investigation of the proposed verification method, focusing on this special case of Human–Robot Interaction (HRI). The findings of this research provide valuable information to the research community, in order to better understand the opportunities and limitations of using haptic devices in telesurgical systems in real-life surgical scenarios.

## New Scientific Results

### Thesis 1

I developed and verified a novel, nonlinear, 8-parameter mass–spring–damper soft tissue model. In contrast to the current models employed, the qualitative advantage of this model is that it represents the soft tissue behavior in both pure relaxation and constant deformation rate compression phases. I showed that in the case of uniaxial deformation, the reaction force from tissue palpation can be estimated with a relative error of 12%. I verified the model for non-uniform surface deformations, showing that below 20% relative deformation, the reaction forces can be estimated with a relative error of 35%.

Related publications: [TA-3, TA-6, TA-7, TA-8, TA-11, TA-13, TA-14, TA-15, TA-16].

### Thesis 2

Based on the concept of Tensor Product modeling, I created the polytopic representation of the nonlinear soft tissue model, and showed that this representation described the soft tissue behavior with sufficient accuracy for controller design. Utilizing the Linear Matrix Inequality method, I designed a controller for the force control task in teleoperation systems. I found that due to the slow poles of the system, the conventional design strategies were not applicable, and I proposed a new approach for designing force feedback control with polytopic representation of the tool–tissue interaction model. I verified the designed controller for robustness in terms of parameter uncertainty and time-delay.

Related publications: [TA-4, TA-5].

### Thesis 3

I designed the evaluation of tissue characterization trials, where based on the outcome of independent test subjects, I experimentally proved that the proposed nonlinear soft tissue model represents the behavior of *ex vivo* tissues both qualitatively and quantitatively. In the case of the force-feedback teleoperation system, 30% of the human operators were able to distinguish between *ex vivo* and artificial soft tissues, which verifies the realistic behavior representation of the nonlinear soft tissue model. Furthermore, 60% of human operators mistook the virtual models of artificial soft tissues for *ex vivo* models in force-feedback teleoperation scenarios, when the quantitative mechanical parameters of the virtual models were alike. This validates the use of artificial soft tissue samples in education and research.

Related publications: [TA-1, TA-2]

Other publications related to the Ph.D. thesis and the accompanying research work:

[TA-9, TA-10, TA-12].

## Applicability of the Results

The results of Thesis 1 showed that the proposed model can be employed as a sophisticated tool to estimate the force response of the tissue during surgical manipulations. This allows one its integration to model-based control approaches and into surgical simulators for training and education. However, there is still room for the investigation of the case of complex surface deformation scenarios, the real-time prediction of the reaction force based on on-line deformation shape measurement and the modeling of more sophisticated surgical interventions. The extension of the model to multidimensional deformation, and the consideration of lateral forces during the manipulation also pose an interesting research topic, as well as its integration into coupled problems including invasive, biochemical and thermo-mechanical interactions.

The control architecture proposed in Thesis 2 can be generalized for various tissue manipulation tasks during robotic surgery. The implementation of this method into supervised teleoperation systems can enhance their performance both in terms of precision and robustness, and the research can be extended for the investigation of bilateral teleoperation scenarios with haptic feedback. Therefore, the experimental validation of the control algorithm is a first step, utilizing it both in virtual and *ex vivo* surgical scenarios. This requires the model of the discrete-time PDC observer in the simulation environment.

The methodology discussed in Thesis 3 allows one to create a general database of different *ex vivo* tissue models and widely-used silicone materials for phantom generation and assembly. It can also aid the field of tissue engineering to provide realistic tissue samples for modeling and planning surgical interventions. There is a need for creating a methodology for the development of artificial silicone samples, mimicking the mechanical behavior of various soft tissues, based on the parameters acquired for the proposed nonlinear soft tissue model. The implementation of the approach to more complex virtual surgical scenarios is possible, while the validation of the method using different haptic devices is also a promising further application of the results.

The major topics discussed in this Thesis work are utilizing the results in a hierarchical way: the proposed and verified soft tissue model is used for the model-based controller design, while the polytopic representation is utilized for the tissue characterization trials in the implementation phase. While strongly connected, these topics can be further developed independently as well. This allows one to

extend the scope of research and use the results in other fields of studies outside medical technologies.

While this work tends to give a solution to the research goals stated in this document, naturally, new questions arose during the elaboration on the topics, along with challenges to be addressed in the field of surgical robotics. This work provides an outlook on these issues, providing an extensive literature reference for those interested.

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