

Towards Semantic Simulation for Patient-Specific Surgery Assistance

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Abstract. Surgery simulations can provide useful ancillary information for intervention planning, diagnosis and therapy. However, simulation support is rarely established in the clinic, since numerics expert knowledge is still essential for setting up meaningful simulation scenarios. We want to address this problem by means of a system which semantically describes the adequate numerics expert knowledge, such as modeling parameters, algorithm properties, and structural dependencies. Using this setup and thereon-based semantic reasoning, we want to enable flexible, automated, and patient-specific simulations for surgery assistance.

Keywords: Surgery Assistance; Semantic Reasoning; Semantic Simulation; Numerics; Uncertainty Quantification;

1 Introduction

IT-based support can provide surgeons with useful additional information, e.g., through surgery simulations. Nevertheless, to date, biomechanical simulations are rarely established in the operation room (OR) or in the context of clinical research. This is mainly due to their complexity, which entails that handling the respective simulation environments and simulation tools is usually too difficult for non-simulation-experts, like surgeons and medical staff in the OR. Also, to best set up simulations and to maximally benefit from them, an in-depth simulation experience and numerical knowledge is needed.

So far, we exemplarily considered the specific case of mitral valve reconstruction (MVR) surgery [2], which is a complex operation that we want to support through providing surgeons with biomechanical surgery simulation scenarios [8]. We have hence set up a complex, integrated, automated pipeline to process patient data and MVR expert knowledge into an MVR surgery simulation scenario, see [6], [5]. This scenario is then executed by our MVR simulation application which is based on the Finite Element Method (FEM) [7]. When conceptualizing and implementing this MVR simulation application, we made use of our numerical expert knowledge and experience in order to, e.g., choose the best-suitable

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numerical solvers and preconditioners for the given problem formulation, or to specify the discretization error in dependence of minimum accuracy and best computational performance.

Going beyond MVR surgery, of course, one can set up such surgery-specific simulation applications for different types of surgeries separately. However, using general numerics knowledge and a structured representation of the experience with numerical algorithms and their properties, it is possible to define strong, general dependencies between miscellaneous parameters in the context of the surgery-dependent mathematical model setup on the one side, and the derived simulation properties (and even the respective surgery simulation results) on the other side. Accordingly, large parts of the MVR simulation experience could be transferred to other potential future surgery simulation setups: for instance, the biomechanical contact model and/or the analytical process of setting it up and calibrating it on the basis of morphological data and relations.

Semantically describing such analytical features, numerical algorithm properties and structural dependencies, and formulating explicit rules, e.g., in terms of decision trees, see Fig. 1 and 2, enables automatically inferred simulation setups for arbitrary surgery simulation types, or even for simulation-based optimization.

Given that some properties and variables are subject to uncertainties, which can be modelled via probabilistic distributions [4], adding a semantic representation of methods for uncertainty quantification (UQ) seems reasonable, too; see the boxes marked with the UQ attribute in Fig. 1 and 2. Knowing the respective stochastic distributions of these properties as part of the semantic model will then allow to quantify the uncertainties in the emerging simulation results.

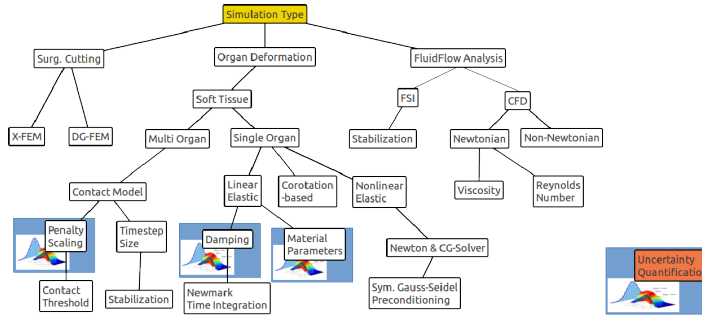


Fig. 1. Sample dependencies tree to deduce simulation setup properties: In order to set up a simulation scenario, the tree is passed through from the root to the tip, and the respective properties and parameters are instantiated or set to fixed values. Some parameters that can generally be subject to uncertainties are furnished with the UQ attribute, such that the respective stochastic parameter distribution (if known from experience) can automatically be included and thus is accounted for in the simulation.

Hence, our idea and long-term vision is a collection of quantified numerics expert knowledge, and a semantic description of this knowledge, which comprises

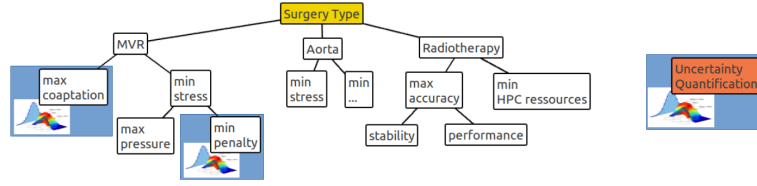


Fig. 2. Sample dependencies tree to deduce simulation-based optimization parameters: To solve optimization problems, parameters may be furnished with an optimization attribute, i.e., a minimum/maximum of these properties can be computed according to given (semantically represented) goal functionals. E.g., in MVR surgery, through annuloplasty the coaptation should be maximized while stresses should be minimized.

numerical methods, parameters, properties, and dependencies. With this setup and thereon-based semantic reasoning, the accessibility to and the setup interface for simulation engines will be simplified, and general types of surgery simulations can be set up fully-automatically; Fig. 1. Moreover, optimization with respect to specified goal functionals can take place (“*What is a critical stress threshold value?*”, or “*How large should the coaptation be after MVR?*”), and uncertainties can be considered (“*Which variables are subject to uncertainty?*”), while the available High-Performance Computing (HPC) infrastructure is maximally exploited (“*How many compute servers does real-time require?*”); Fig. 2.

Currently, to the best of the authors’ knowledge, there is no comparable approach published, which thus aims at simplifying the usability of surgery simulations via a semantic representation of simulation properties and an underlying numerics properties decision tree.

2 Suggested Methodology

In order for setting up a such system, we suggest proceeding as follows.

First, a structured collection of expert domain knowledge and experience in numerics has to be set up, e.g., by means of representing results from previous works or by mining results from other research groups. Here, connections and dependencies between the following features have to be established:

- biomechanical models, e.g., elasticity, fluid flow, fluid structure interaction;
- boundary conditions, e.g., displacements, fixation, pressure, contact;
- model parameters and variables, e.g., damping, penalty scaling, material properties, sources for uncertainties and respective probability distributions;
- solution algorithms, e.g., time integration methods (Crank-Nicolson, Newmark), space discretization methods (FEM), solvers (CG, GMRES), preconditioners (Gauss-Seidel, AMG);
- methods for UQ, e.g., Monte Carlo or Polynomial Chaos extension;
- algorithmic properties, e.g., convergence, stability, performance, accuracy;
- simulation-based optimization, e.g., description of goal functionals, min-max-dependencies, available/required HPC resources;

In describing the knowledge, one might primarily stick to the modeling alphabet of the Medical Simulation Markup Language (MSML) [10], and extend it with additional specific numerical features, such as in Fig. 1 and 2.

Secondly, the thus assembled factual numerics and modeling knowledge (which is interconnected via respectively defined dependencies) has to be represented semantically (i.e., modelled, e.g., using Protégé), and then needs to be related and conforming with some upper or top-level ontology, such as the Basic Formal Ontology (BFO) [1]. Through a such top-level ontology it is then to be linked to a surgical domain ontology, such as the Foundational Model of Anatomy (FMA) for surgery-relevant properties. Eventually, our numerics dependencies structures and concepts should thus be derived and represented as a refinement of the BFO, as a numerical modeling and simulation domain ontology, and thus allow the two domain ontologies to interconnect and communicate; see Fig. 4.

Theorem-based, formal rules (inference methods) can be set up to constitute interconnecting dependencies, see Fig. 4. Using, e.g., SWRL to define these rules enables semantic reasoning via a semantic reasoning engine, such as Hermit, cwm or Data-fu [9]. A such reasoner then executes the rules on respectively given patient data in order to thus derive appropriate simulation scenarios.

3 Preliminary Results

Following the suggested methodology, on the one side, we have set up a first simple numerics and modeling dependencies tree, Fig. 1, yet so far without semantic representation and without links to an upper ontology. On the other side, we exemplarily consider two sample surgery scenarios – MVR cardiac surgery and liver surgery –, for both of which we have manually linked the respective surgical and anatomical features to entities and relations in the FMA domain ontology.

Subsequently, – in our preliminary system – we have manually set up mappings between these two, see Fig. 3. This setup enables numerical models and corresponding simulation scenarios to be inferred from anatomical or surgical situations, by simply going through the anatomical or surgical structured dependency tree, and having the respective numerical property set in the numerics

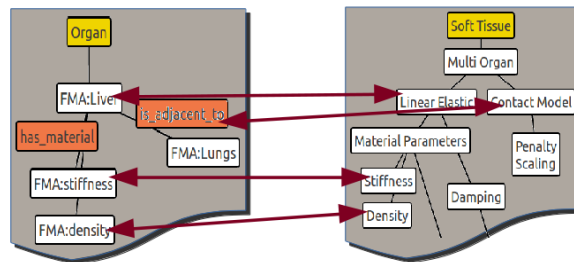


Fig. 3. Sample coupling of two property and dependency structures: anatomical and surgical properties/relations couple with numerics and modeling properties/relations.

FMA:Liver	is_a	FMA:Organ			
	consists_of	FMA:SoftTissue	has_property	FMA:Stiffness	
			has_property	FMA:Density	
	is_adjacent_to	FMA:Lung	is_part_of	FMA:RespiratoryTract	
	has_image	FMA:CTscan			
SoftBody	has_a	ElasticityModel	is_a	LinearElasticModel	has_a
					MaterialStiffness
	has_a	ContactModel	has_a	ContactBoundary	has_a
			has_a	PenaltyScaling	
	has_a	Geometry	originates_from	CTscanSegmentation	
Rule1:	Respiration	causes	PressureGradients		
Rule2:	PressureGradients	can cause	BoundaryConditions.		
Rule3:	SoftTissue	can be	Healthy or Pathologic.		
Rule4:	Healthy SoftTissue	is less stiff than	Pathologic SoftTissue.		

Fig. 4. Sample extract of how semantic representations of medical or surgical entities/properties (upper box) are linked to numerics and modeling features (middle box) on the implementation level. Colors and arrows indicate the respective links or rules.

properties decision tree. Properties or parameters which are not instantiated like this will be set to default values. See Fig. 4 for an implementation example.

Finally, the semantic and numerical model collaborate in that the numerical model and the thus resulting simulation scenario are set up by means of passing through the numerics properties decision tree from the root to the tip of each branch, thereby scanning the respectively set parameters and properties.

Ongoing, we work on having this preliminarily mapped interconnection facilitated by means of links to the BFO, which thus assists in making communication between and among the two domain ontologies, namely (1) the FMA, and (2) our numerical modeling and simulation ontology. Based on the hence provided common ontological architecture, a semantic reasoner can then draw conclusions and infer consequences of assertions (i.e., of properties and respective mappings).

4 Discussion and Outlook

With the implementation of a such semantic surgery simulation system that is based on profound, structured numerics knowledge, we expect to enable a general approach to set up patient-specific surgery simulations in the OR (without any personal specific numerics expert knowledge).

We hence aim at fostering and simplifying the usability of surgery simulations via a *semantic representation of numerics and simulation properties* and an *underlying numerics properties decision tree*, which is *linked* to a corresponding *semantic representation of anatomical and surgical properties*.

Being based on general numerical properties and dependencies, this semantic surgery simulation system is capable of increasing the simulation efficiency, e.g., by best exploiting available compute infrastructures, and best-tailored scenario setups. It thus saves time and cost for simulation, and also obviates the need for a numerics expert in the OR. Moreover, added value for patients and surgeons can be expected through suggested simulation-based optimization and

thus objectivation of surgical treatment and patient care. Generally, an ontological representation of our work also allows for sharing and communicating knowledge and thus fosters the sustainability.

In order for obtaining a first properly operational prototype, we see the following challenges and bottlenecks to progress: (1) Lots of abstraction work and respective modularization of miscellaneous simulation and simulation preprocessing software components is still needed. We therefore aim at learning from the concrete MVR case and at transferring and generalizing the gained experience. (2) A generalization of the simulation properties in a research context is only achievable up to a certain level as from which on further completion is a rather routine piece of work. We aim at achieving generalization for a few sample surgery scenarios to show general feasibility and flexibility.

For evaluation, on the one hand, we plan to validate the complete setup by means of surgery application scenarios arising in our research project (e.g., in cardiac, vascular and liver surgery). On the other hand, the methodology and the single components can be evaluated separately, e.g., via reasoning and model comparison (numerics expert vs. reasoning system).

Going further, future work is to cover vascular surgery along with CFD/FSI simulation, in order to demonstrate the flexibility of our approach and to show its extensibility. Topping this system with some machine intelligence may allow for learning and improving the knowledge based on patient or use-case similarities.

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