3D Modeling for Endoscopic Surgery

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ABSTRACT

Surgical training systems based on virtual reality (VR) and simulation techniques may represent a more cost effective and efficient alternative to traditional training methods. Additionally, VR is a technology that can teach surgeons new procedures and can determine their level of competence before they operate on patients. At Forschungszentrum Karlsruhe, a virtual reality training system for minimally invasive surgery (MIS), based on the simulation software *KISMET*, has been developed An overview of the current state of development for the "Karlsruhe Endoscopic Surgery Trainer" is presented. For quick and easy creation of surgical scenes containing deformable anatomical organ models, the spline based modeller *KisMo* has been developed, which generates beside the geometry also a spatial mass-spring network of the objects for the elastodynamic simulation in *KISMET*. The MIS trainer provides several surgical interaction modules for deformable objects like grasping, application of clips, cutting, coagulation, injection and suturing. Additionally it is possible to perform irrigation and suction in the operation area. Active deformable objects are used for the morphodynamic simulation of the stomach and the intestines. Furthermore a hierarchical pulse simulation in virtual arterial vessel trees has been realized, which enables the palpation of the pulse with a force-feedback device. The pulse simulation is coupled with an arterial bleeding simulation, which gets activated by injuries of arteries and stopped by application of clips. The simulation system has been applied to minimally invasive surgery training in gynaecology and laparoscopy. Special attention is addressed to elastodynamically deformable tissue models and geometric modelling techniques for graphical realtime performance.

Keywords: simulation, tissue modelling, deformable tissue models, VR-based surgery training

INTRODUCTION

Minimally invasive surgery (MIS) has been established among surgeons as an elective technique in a number of general surgery interventions. Endoscopic surgery of the abdomen, like gall-bladder and appendix removal, have now become commonly performed surgical operations. However, beneficial to the patients, these techniques require intensive training of the surgeons, practising skills like 3D-orientation, hand-eye coordination and instrument handling. Surgical education has traditionally depended on the apprentice-mentor relationship and is the basis of residency training programs. Physical patient models like the pelvi-trainer lack realistic anatomical features. The concept of virtual reality (VR) surgical simulators is attracting considerable attention. Progress in computing performance allows the development of training systems for endoscopic surgery based on VR technology.

As a basis for our R&D activities, we use the 3D-graphical simulation program *KISMET* [1] (**Ki**nematic **S**imulation, **M**onitoring and Off-Line Programming **E**nvironment for **T**elerobotics), which has been under development at Forschungszentrum Karlsruhe (FZK) for a number of applications. Because of its high quality realtime graphics capabilities and additional features like geometrical and kinematical modelling, multibody-dynamics, and its database concept allowing for multiple detail-levels, it was found to be an ideal platform for computer aided surgical simulation. The software has been improved significantly during the past years to meet the specific requirements of physical model based minimally invasive surgery simulation. Using the advanced capabilities of high-performance graphical workstations combined with state-of-the-art simulation techniques, it is possible to generate virtual endoscopic views of surgical scenarios with high realism.

The "Karlsruhe Endoscopic Trainer"

The MIS trainer produces a synthetic mono or stereo image of the view, which is in reality provided by the endoscopic camera. As a surgeon-computer interface, a "Mechano/Electrical Box" was developed as an artificial cavity together with the correct instrument set so that the interface normally presented to the surgeon is maintained using a physical simulation. This set-up [Figs. 1,2,3] enables following practical exercises:

- coordination of different instruments
- handling of an endoscope mock-up with its corresponding synthetic camera view
- teamwork of surgeon, assistant and cameraman
- simulation of new instrument designs and manipulator control devices
- measurement of handling speeds in a simulated environment

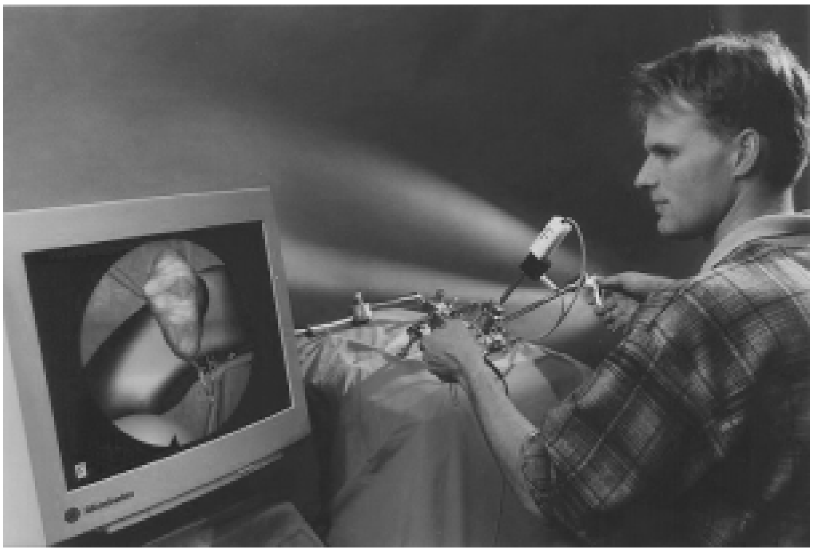
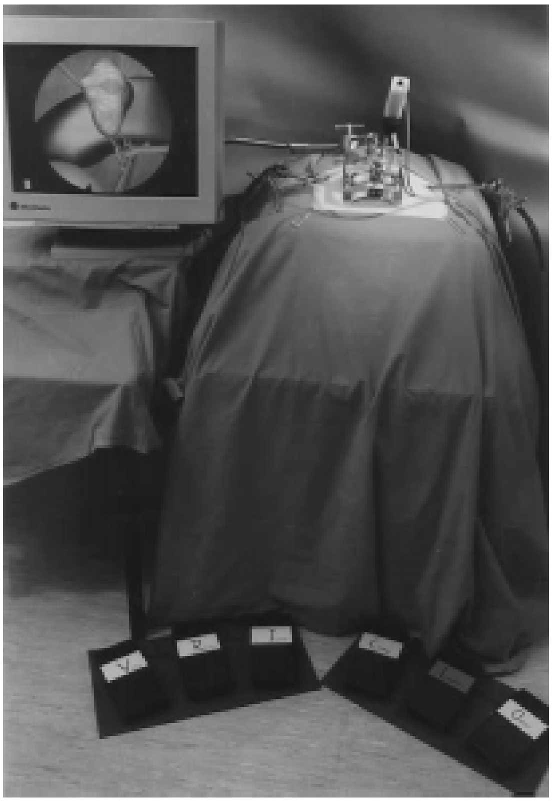


Figure 1:

The MIS training system for VR based simulation of the cholecystectomy surgery scenario.

The design concept of the Karlsruhe Virtual Endoscopic Surgery Trainer takes into account the kinematics of conventional endoscopic handling with four main degrees of freedom (DOF). Furthermore it allows for future extension of the training interface with dexterous instruments with 6 or more joints, i.e. kinematically redundant mechanisms. We have developed simulation techniques which allow the modelling of "virtual tissue" based on a data-model which reflects the physical characteristics of like mass, stiffness and damping of real living tissue. A collision test algorithm detects contact between surgical instruments and the manipulated virtual objects. As a by-product, contact forces between the tissue and the instrument end-effector are calculated which can be used in future surgeon interfaces to drive force-reflecting input devices. An advanced interaction module allows grabbing, cutting, clipping and coagulation of virtual tissue and “organs”.

The trainee surgeon manipulates the instruments in the normal way, and in our case the movements are transferred to the graphics workstation by means of a PC-based joint angle measurement system. The PC provides up to 48 analog 12-Bit input channels and 32-Bits digital input for foot switches. The sensor data are transferred with 50 Hz to the graphics station by means of asynchronous RS-232 communications. We use potentiometers hinged to all internal instrument degrees of freedom together with custom designed and manufactured mechanics inside the "Box" to aquire the relative joint positions. On request of the graphical workstation (data polling), the signals are submitted via serial Interface with 38.400 Bits/sec. The maximum response time delay for aquisition and transmission of one data block is less than 20 ms. In addition to the instrument box, several foot switches are used to control surgical interactions (coagulation) and system control functions (model reset, instrument change).



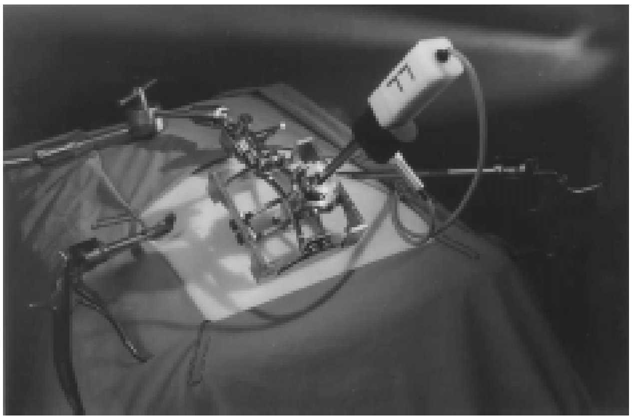


Figure 3 (top): MIS-Trainer "Instrument Box"

Figure 2 (left): MIS-Trainer component overview

SIMULATION TECHNIQUES AND MATHEMATICAL FRAMEWORK

KISMET is implemented under the UNIX (IRIX) and WindowsNT operating systems on a wide range of SGI (VPC 320 and 540, OCTANE, ONYX) and INTERGRAPH high-performance graphics workstations. This configuration allows for synthetic generation of any view in a surgical simulation with interactive rates, depending on the complexity of the models. In our demonstrator, 20 images per second are calculated, using an SGI-Octane/MXE workstation with two 250 MHz Mips R10000 CPU’s. Multiple window display and stereoscopic viewing using shutter glasses are supported by *KISMET* as display options. The objects can be rendered in high quality shaded modes with surface texture, as wireframes, or as transparent models. The display mode can be set interactively as an object attribute for any part and/or for groups of parts.

Our research and software development is currently directed to the simulation of realistic interactions between surgical tools and the organs, which are modelled as deformable bodies. We have developed simulation techniques which allow the modelling of "virtual tissue" based on a data-model which reflects the physical characteristics like mass, stiffness and damping of real tissue [4]. Virtual organ geometry is modelled in *KISMET* as elastic POLYHEDRON, NURBS or VOLUME objects. The control points of the object surface form together with additional internal nodes an elastic 3D mesh of virtual mass points (nodal network), which are interconnected by virtual springs with damping elements [Fig. 4]. The equation of motion for the dynamic spring/mass-node system is solved by discrete integration as a coupled system of second order ordinary differential equations (*Lagrange* equation)

$$m_i \frac{d^2 \underline{x}_i}{dt^2} + \gamma_i \frac{d\underline{x}_i}{dt} + \underline{g}_i(t, \underline{x}_i) = \underline{f}_i(t, \underline{x}_i) \quad (1)$$

$\underline{x}_i$ denotes the cartesian coordinates of the mass node; m_i the mass of the node; γ_i the damping coefficient; g_i the sum of all inner forces at node *i*, and f_i all external forces at the node. For the sum of all inner forces acting on the mass node we can use the set of equations:

$$\underline{g}_i = \sum \underline{s}_k \qquad \underline{s}_k = \frac{c_k \cdot e_k}{\|\underline{r}_k\|} \cdot \underline{r}_k \quad (2a\text{-}d)$$

$$e_k = \|\underline{r}_k\| - l_k \qquad \underline{r}_k = \underline{x}_j - \underline{x}_i$$

Here, $\underline{s}_k$ is the inner force at mass node *i*, caused by spring *k*; c_k denotes the spring stiffness of spring *k*; e_k is the absolute value of the deformation from its initial position (i.e. the deformation); $\underline{r}_k$ is the distance vector between the two nodes delimiting spring *k*; $|\underline{r}_k|$ is the absolute scalar of the distance for spring *k*, and $\underline{x}_j$ denotes the cartesian position vector for mass node *j*, which is connected through spring *k* with mass node *i*.

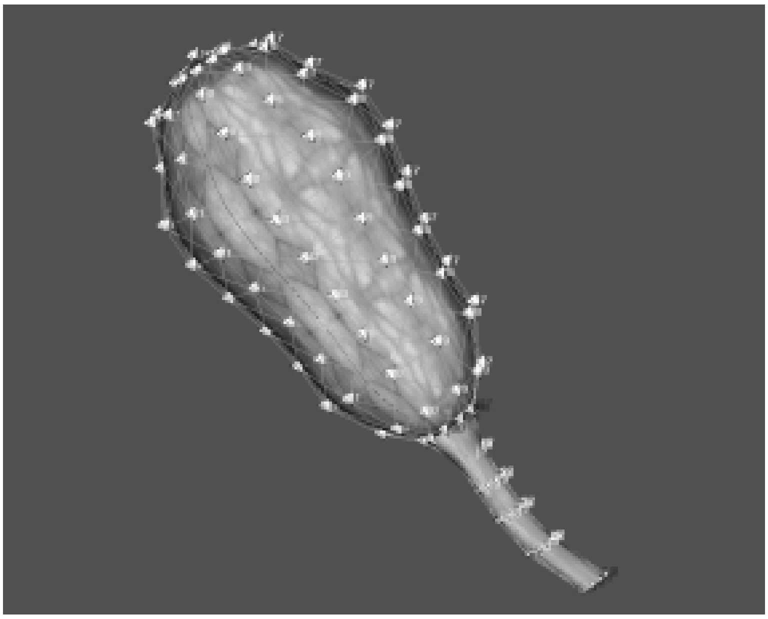


Figure 4:

A nodal mesh of virtual mass nodes interconnected through spring with damping is used for modeling of deformable tissue objects ("organs").

For performance reasons, we use a simple, explicit Newton-Euler method for integration:

$$\underline{h}_i^{\,t} = \underline{f}_i^{\,t} - \gamma_i \cdot \underline{v}_i^{\,t} - \underline{g}_i^{\,t} \qquad \left(\underline{v}_i^{\,t} = \frac{d\underline{x}_i^{\,t}}{dt} \right) \quad (3a\text{-}e)$$

$$\underline{a}_i^{\,t} = \frac{d^2 \underline{x}_i^{\,t}}{dt^2} = \frac{\underline{B}_i \cdot \underline{h}_i^{\,t}}{m_i}; \qquad \underline{v}_i^{\,t+\Delta t} = \underline{v}_i^{\,t} + \Delta t \cdot \underline{a}_i^{\,t}; \qquad \underline{x}_i^{\,t+\Delta t} = \underline{x}_i^{\,t} + \Delta t \cdot \underline{v}_i^{\,t+\Delta t}$$

here, $\underline{h}_i$ is the sum of all forces (inner and external) at mass node *i*, $\underline{a}_i$ is the acceleration vector for node *i*, $\underline{v}_i$ the velocity vector at node *i*, Δt is the integration time (i.e. the sampling time constant of the system), and $\underline{B}_i$ denotes the boundary matrix (degrees of freedom) for node *i*.

The system is stable if the criterion (numerical stability criterion) [5]

$$d_s > \frac{\Delta t \cdot k}{2} - \frac{m}{\Delta t} \quad \text{or} \quad \Delta t < \frac{d + \sqrt{d^2 + 2mk}}{k} \quad (4a,b)$$

is fulfilled. Here d_s denotes the system damping, k denotes the dominating spring stiffness at each mesh node.

Elastodynamic parameters: Basic research on elastodynamic behaviour of living tissue [7] has shown, that real tissue structure is non-linear and anisotropic. The non-linear shape of the stress-strain curves (Fig. 5) can be well approximated by an approach using a 3^{rd} degree polynomial curve. The polynomial was split in a scaling part (scaling value E) and a shape part, described by the shape factors P_1 and P_2 as shown in the equation

$$\sigma = E \cdot \varepsilon \cdot (1 + P_1 \cdot \varepsilon + P_2 \cdot \varepsilon^2) \qquad (5)$$

(σ: compressive stress, ε: compressive strain, E: scaling value, P_1, P_2: non-linear shape factors)

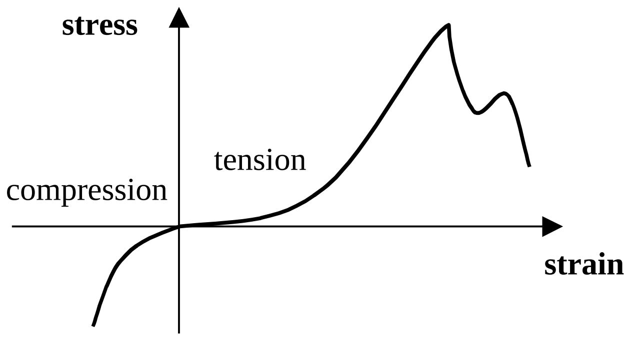


Figure 5 : typical stress-strain-diagram for biological media

Discussion of the "full dynamic mesh method": However, the full dynamic simulation model as described has the advantage of being capable to simulate non-linear and anisotropic tissue characteristics, but it also has the drawback of a high computational demand and the risc of numerical instability. Therefore we have a second calculation method in the *KISMET* software, the *elastostatic finite element method* (FEM), this method is further discussed in [6].

Principle of the FEM method: The basic equations for the deformable mesh system with N nodes can be written for the FEM approach as

$$\mathbf{Ku} = \mathbf{f} \qquad (6a) \qquad \text{and} \qquad \mathbf{K}^{-1}\mathbf{f} = \mathbf{u} \qquad (6b)$$

where $\mathbf{u}$ is the deformation vector (dimension 3N x 1), $\mathbf{f}$ is the force vector (3N x 1) and $\mathbf{K}$ (dimension 3N x 3N) is the stiffness matrix, $\mathbf{K}^{-1}$ denotes the inverse stiffness matrix.

Realtime calculation of the elastostatic loadcase: Using in a first step the inverse stiffness matrix $\mathbf{K}^{-1}$ to generate an equation system for the unknown force at the interacting node k, the solution of equation (7) (e.g. using the *Gauss method*) with a given nodal deformation vector $\mathbf{u}$ (load case) leads to the force solution vector $\mathbf{f}_\mathbf{k}^\mathbf{e}$ for the deformed node k. Using in a second calculation step the resulting force vector $\mathbf{f}_\mathbf{k}^\mathbf{e}$ with equation (4b) to multiply with the inverse stiffness matrix $\mathbf{K}^{-1}$, we can now calculate the deformation vector $\mathbf{u}$ for the complete system.

$$\overbrace{\begin{bmatrix} k^e_{1,1} & .. & .. & .. & .. \\ .. & .. & .. & k^e_{j,k} & .. \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & k^e_{N,N} \end{bmatrix}}^{\mathbf{K}^{-1}} \overbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ f^e_k \\ 0 \end{bmatrix}}^{\mathbf{f}} = \overbrace{\begin{bmatrix} u^e_1 \\ .. \\ .. \\ .. \\ u^e_N \end{bmatrix}}^{\mathbf{u}} \qquad (7)$$

Only those columns of the matrix system have to be multiplied, which correspond to the deformed mass node. With multiple deformed mesh nodes (i.e. multiple interactions), the principle of *superposition* is used, i.e. we can calculate the complete deformation vector $\mathbf{u}$ through addition of the single-deformation solutions. The major advantages of the approach as described, are the stability of the numerical system and the numerical performance.

Offline-calculation of the (inverse) stiffness matrix: The inverse stiffness matrix can be derived in a (non-realtime) pre-computation step from the full dynamic mesh model by application of unit forces $\mathbf{f}_{\mathbf{k}}^{\mathbf{e}} = \{(1,0,0),(0,1,0),(0,0,1)\}$ for each node in the mesh. The resulting deformation vectors $\mathbf{u}^{\mathbf{k}}$ for each node in the mesh exactly correspond to one column in the inverse stiffness matrix $\mathbf{K}^{-1}$. This matrix is stored for each model and reloaded during object initialisation.

Optimisation (FFE-Method): It is sufficient to calculate the deformation of only the surface nodes (outer nodes) in the volumetric 3D mesh, because only these nodes can interact with surgical instruments and only these nodes are visible. By means of mesh sorting or model condensation, we get the following form of the matrix system:

$$\left[\begin{array}{c|c} \mathbf{K}_{\mathbf{o}}^{-1} & \mathbf{K}_{\mathbf{oi}}^{-1} \\ \hline \mathbf{K}_{\mathbf{io}}^{-1} & \mathbf{K}_{\mathbf{i}}^{-1} \end{array}\right] \left[\begin{array}{c} \mathbf{f}_{\mathbf{o}} \\ \hline \mathbf{f}_{\mathbf{i}} \end{array}\right] = \left[\begin{array}{c} \mathbf{u}_{\mathbf{o}} \\ \hline \mathbf{u}_{\mathbf{i}} \end{array}\right] \tag{8}$$

It is obvious that we can achieve a great reduction in memory and as well a gain in computational performance using mesh condensation.

Discussion of the FEM/FFEM method: The calculation of the complete matrix system is performed in a single calculation step, i.e. there is no numerical iteration or integration necessary. The system is inherently stable. As a drawback it should be noted, that the method as described solves only for (locally) linear deformations.

Further calculations: A collision test algorithm detects contact between surgical instruments and the virtual organs. The algorithm allows for realtime simulation of tissue elasticity. The algorithm used in *KISMET* allows for realistic interaction (deformations) between surgical instruments and tissue surfaces in the virtual surgery scenario. As a by-product, contact forces between the tissue surface and the instrument end-effector are calculated, which can be used to drive a force-reflecting surgeon interface. This feature will be used for future tactile feedback in our MIS trainer.

MODELING AND SIMULATION OF SURGICAL SCENARIOS

Kinematics: The kinematics of a mechanical manipulator can be modelled in *KISMET* as an open or closed-loop articulated chain with several rigid bodies (links) connected in series by either revolute or prismatic joints, driven by actuators. High-level joints (planar, spheric etc.) are modelled with combinations of the two basic types. We use formalised methods to model the kinematical structure of mechanisms to provide a systematic and generalised approach to define and calculate mechanism motion with respect to a fixed reference frame. Thus, *KISMET* was used at FZK to support the design of the instruments and medical manipulators used in the ARTEMIS telesurgery system [2]. The kinematical simulation of these multi-link mechanisms allows detailed studies during the design stage. The behaviour of these mechanisms can easily be modified by interactive modification of the kinematical design parameters. The influence of machining errors in the range of microns has been studied with *KISMET* by a tolerance analysis. Geometrical optimisation has been carried out in order to avoid internal collisions in the mechanisms [3].

Geometry: Geometrical models of the surgical environment, i.e. the organs, cannot be easily modelled with regular shape primitives. Experimentally, we have used commercially available free-form surface modellers for geometry modeling of tissue and organ models. In close co-operation with medical staff from University Tübingen (Prof. Buess), we have developed surgical scenarios of the human digestive system and another one of the upper abdominal organs which is mainly used in the laparoscopic surgery trainer project showing the organs and conventional instruments relevant for the colecystectomy operation (removal of the gall-bladder).

For tissue modelling we use in *KISMET* hybrid POLYHEDRON-, NURBS- and VOLUME-geometry representations.

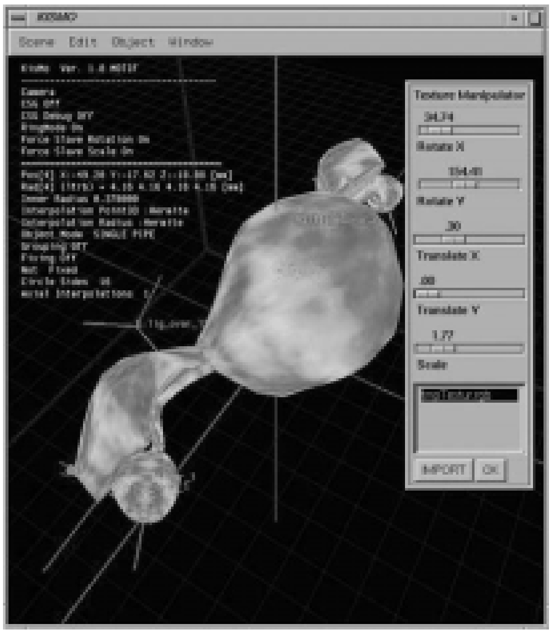


Fig. 6 : Modeling the uterus and ovarii

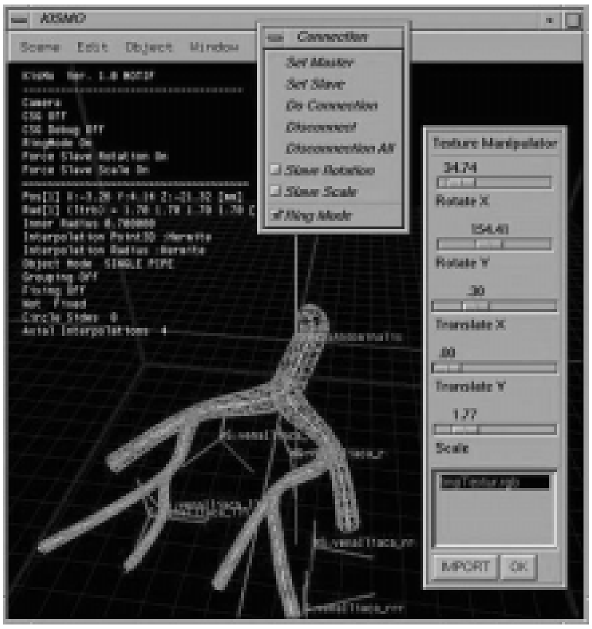


Fig. 7 : Modeling the venal tree

The KisMo modeller: As an additional modeling tool, we have developed the spline-based, interactive, graphical modeller ***KisMo*** (*Kis*met *Mo*deller for elastodynamics objects and scenes for *KISMET*) for specifying the 3D *geometry* and *elastodynamical* parameters of organ models, which are connected with each other to complete surgery scenes. Note that *KisMo* is running on SGI UNIX-workstations and also on Windows-NT. Figs. 6 and 7 show a modeling session with *KisMo* of an arterial tree and the uterus. As a feature in *KisMo* we have added real-time volume rendering without need of any special hardware. Now it is possible to model interactively patient-specific organ models. Figures 8 and 9 show the two rendering methods, with the moveable slices and as a volume block.

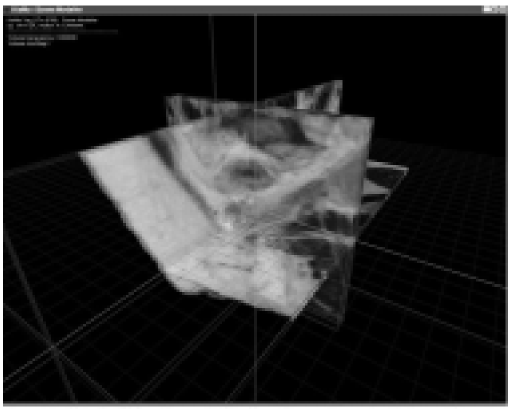


Fig. 8: Volume rendered with moveable slices

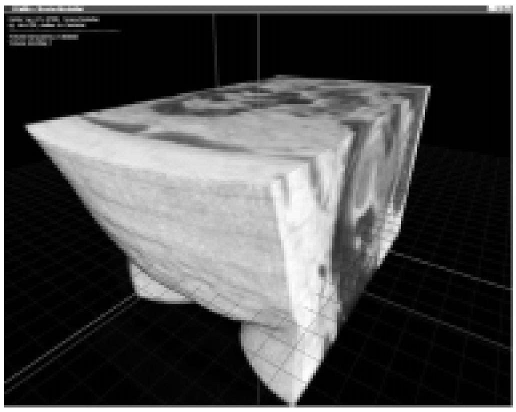


Fig. 9: Volume rendered as a block

Using *KisMo*, a new virtual surgery training environment has been created for the minimally invasive surgery in gynaecology in close co-operation with medical staff from University Kiel (Prof. Mettler). Fig. 10 shows a training session with the *Gynaecology Trainer*.

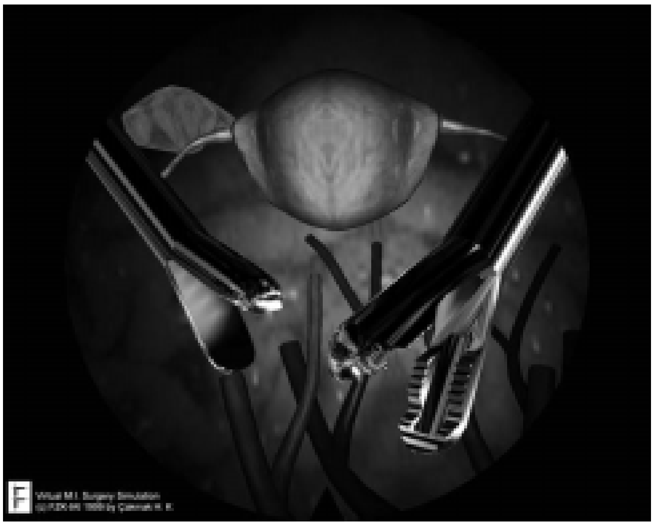


Figure 10 :

The gynaecology surgery scenario as modelled in *KisMo*. The uterus, ovarii, tubes, intestines and the arterial and venal tree have been modelled.

SIMULATION OF SURGICAL INTERACTION

Fig. 11 demonstrates the basic interactions with deformable organ models in real-time. It is possible to deform, grasp, clip and cut into virtual tissue. We demonstrate these steps with the simulation of ovarial sterilisation. After the two clips are places correctly onto the ovarial tubes, the cut is performed.

Fig. 11 : Basic surgical interactions

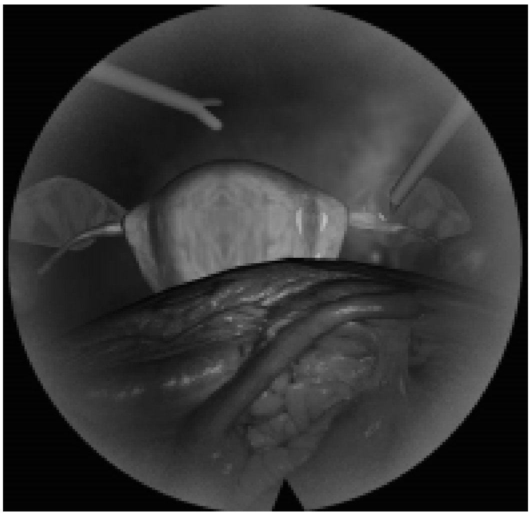


Fig. 12 : Simulation of steam / smoke

We have developed a new method for visualisation and animation of smoke/steam without need of any special 3D texture memory hardware and built it into the MIS-trainer. Using animation techniques for the geometry and the textures, we enable the rise of smoke at the beginning of the coagulation and the fading away of smoke after stopping the coagulation. The endoscopic lense will steam up depending on the coagulation time and the smoke density. Figure 12 shows a snapshot of the MIS-trainer during coagulation.

After an injury of an arterial vessel, the lost blood is accumulated in the virtual body (Fig. 13). After stopping the arterial bleeding with a clip, the surgeon has to perform irrigation and suction of the blood and/or water for cleaning. We have created new instruments for irrigation and suction. Note the deformation of the uterus after being hit by water particles in Fig. 14. The height, colour and transparency of the accumulated fluid in the virtual body is calculated dependent on the properties of blood and water. Additionally ripple effects and splashing water drops on the pool surface during irrigation have been realised. The motion of instruments inside the pool causes also ripple effects. Also note the reflection of the scene on the pool surface.

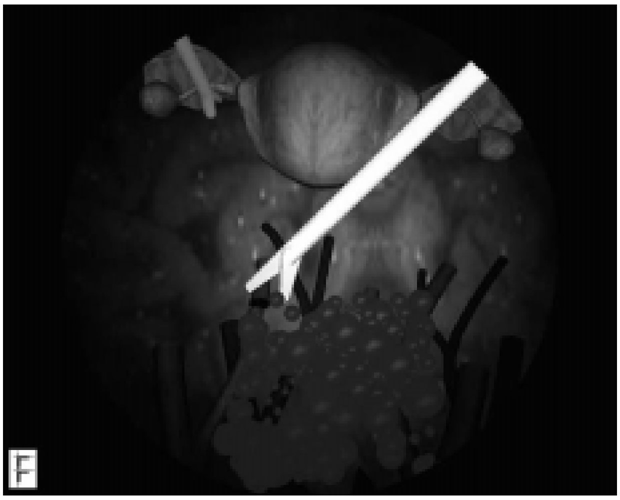


Fig. 13 : Simulation of arterial bleeding

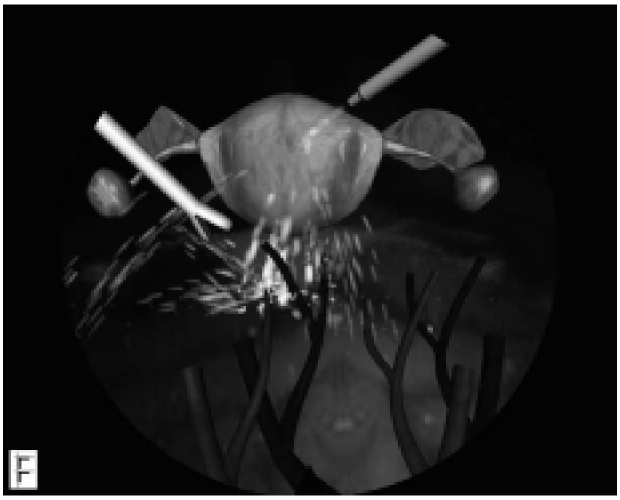


Fig. 14 : Irrigation and suction

We have developed a simulation method for arterial bleeding after any arterial injury using a particle system. The position and direction of bleeding is determined by the cut of the artery. We use a particle system with considering gravity forces and forces between the particles. The motion of the particles obey Newton's law of motion. A database contains information about the vessel hierarchy, so that bleeding can be stopped by setting clips at the correct side.

We define the simulation of autonomous motion of organ models as morpho-dynamics simulation. As a first step we have realised a simulation of the human arterial pulse. A database contains information about the vessel hierarchy, heartbeat rate, speed of pulse and the forces on the vessel walls. The simulation is performed by the propagation of pulse waves through the virtual arterial tree. Note that we have combined the arterial bleeding with the pulse simulation. We use the method of "directed force waves" to animate the motion of intestines and the stomach. It is possible to set force, wave speed, and other parameters to setup the desired motion.

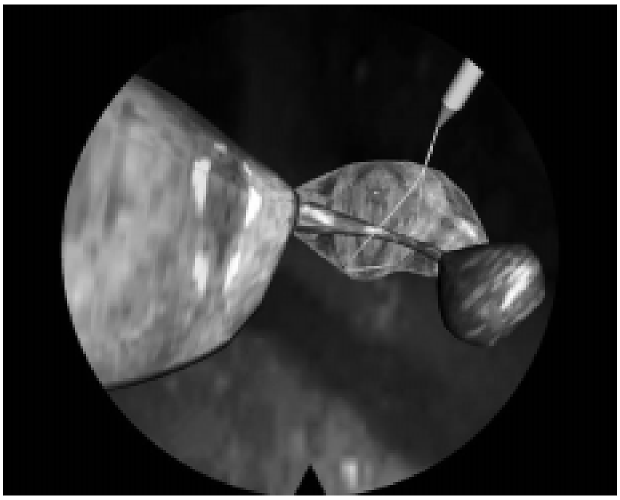


Fig. 15 : Suture and sling simulation

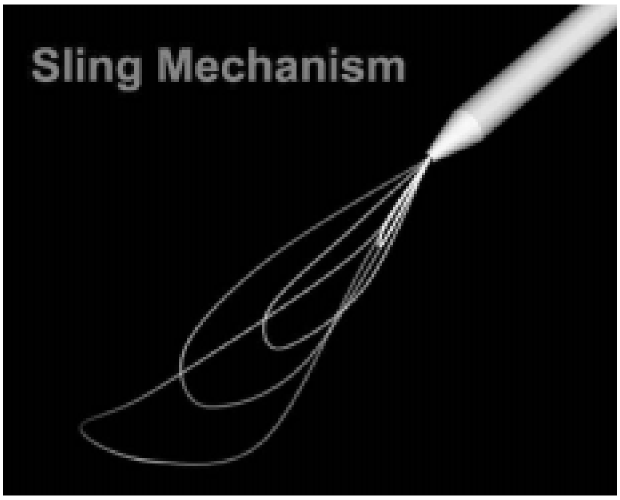


Fig. 16 : The sling mechanism in motion

The geometry and the kinematics of the sling-instrument was designed (Fig. 15). The effector (sling) is modelled as a deformable object. Note the sling mechanism in Fig. 16.

CONCLUSION

It was demonstrated that *KISMET* can be used effectively in medical virtual reality scenarios with high graphical realism during planning, teaching and surveillance of minimally invasive surgery procedures :

- Development of a Virtual Reality abdominal surgery training system.
- 3D-geometric, kinematic and multibody-dynamics simulation, animation and analysis of complex mechanisms during the design phase of new surgical instruments and medical manipulators
- Operation room scenario simulation
- Realtime visualisation of voxel-volume datasets using 3D-texturing techniques
- High-quality 3D-models of the human abdominal anatomy have been created

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