Computer Assisted Prostate Surgery Training

M. A. Padilla Castañeda, F. Arámbula Cosío

Laboratorio de Imágenes y Visión,
CCADET, UNAM,
Universidad Nacional Autónoma de México,
México, D.F., 04510
{padillac, arambula}@aleph.cinstrum.unam.mx

Abstract. In this work is described the development of a computer simulator for training on Transurethral Resection of the Prostate (TURP) based on a computer model of the prostate gland which is able to simulate, in real time, deformations and resections of tissue. The model is constructed as a 3D mesh with physical properties such as viscosity and elasticity. We describe the main characteristics of the prostate model and its performance. The prostate model can also be used in the development of a Computer Assisted Surgery system designed to assist the surgeon during a real TURP procedure. The system will provide 3D views of the shape of the prostate of the patient, and the position of the surgical instrument during the operation. The development of new computer graphics models which are able to simulate, in real time, the mechanical behavior of an organ during a surgical procedure, can improve significantly the training and execution of other minimally invasive surgical procedures such as laparoscopic gall bladder surgery.

1 Introduction

Computer assisted surgery (CAS) and medical robotics systems share the common objective of providing the surgeon with different levels of automatic assistance during planning and execution of a surgical procedure. This is achieved through the integration of: Measurements taken on medical images; Three dimensional (3D) tracking or positioning systems; Computer vision and graphics techniques; and Robotics techniques. Computer assisted and robotic surgery systems differ in the assistance provided during execution. A computer assisted system provides image or model based guidance to the surgeon inside the operating site using a non-contact tracking device such as an optical tracker, while the whole procedure is performed manually by the surgeon [1]. A robotic surgery system provides guidance to the surgeon using a mechanism which can be passive or motorized in which case some or all of the surgical actions are performed by the robot [2][3].

Medical robotics surgery systems can be classified according to the level of automatic assistance provided to the surgeon. Passive surgery assistant robots provide passive guidance to a surgeon who performs all the surgical operations manually. Active assistant robots use motorized mechanisms to perform surgical operations under the supervision of the surgeon. Synergetic assistant robots use motorized mechanisms to produce active constraints which limit the movements of the surgeon to safe regions inside the operating site [4]. In Fig. 1 is shown the active assistant robot for Transurethral Resection of the Prostate (TURP) [5].

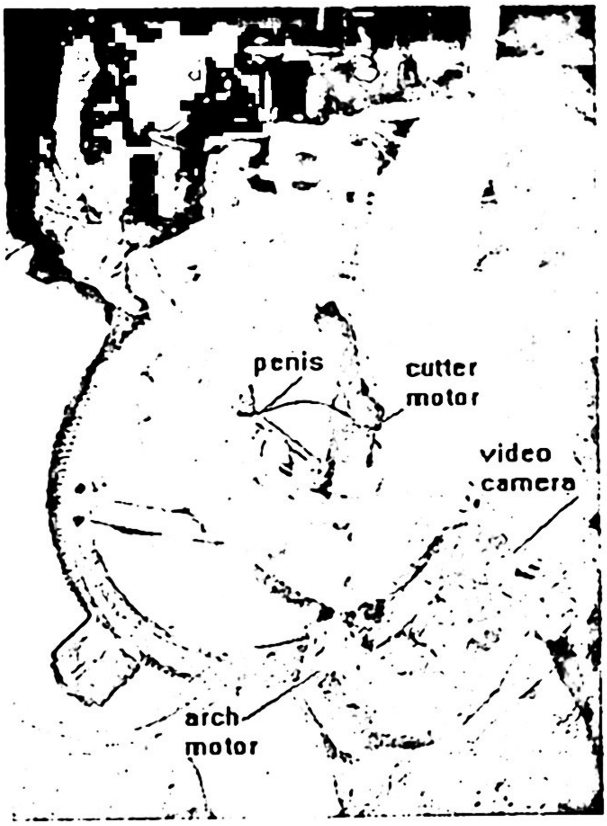

Fig. 1. Assistant robot for prostate surgery

Among CAS systems we have computer simulators for surgeon training and assistance. A computer simulator provides a realistic environment for intensive training of the skills needed for a given surgical procedure. During the execution of a real procedure, the computer model of the organ of the patient can also be used to monitor the progress of the operation. Computer simulators for surgery will significantly benefit from the development of computer models of human organs able to be deformed and resected. In the following sections we present a deformable model of the prostate for TURP surgery simulation.

2 Transurethral Resection of the Prostate

The prostate is a chestnut size gland, located just below the bladder, surrounding the urinary duct of human males. As part of the ageing process the prostate grows and, in some cases, obstructs the urinary flow. This is a common illness in men more than 50 years old. Enlargement of the prostate is treated by surgically removing the obstructing tissue in order to reestablish the free flow of urine. In Fig. 2 is shown the basic anatomy of the prostate.

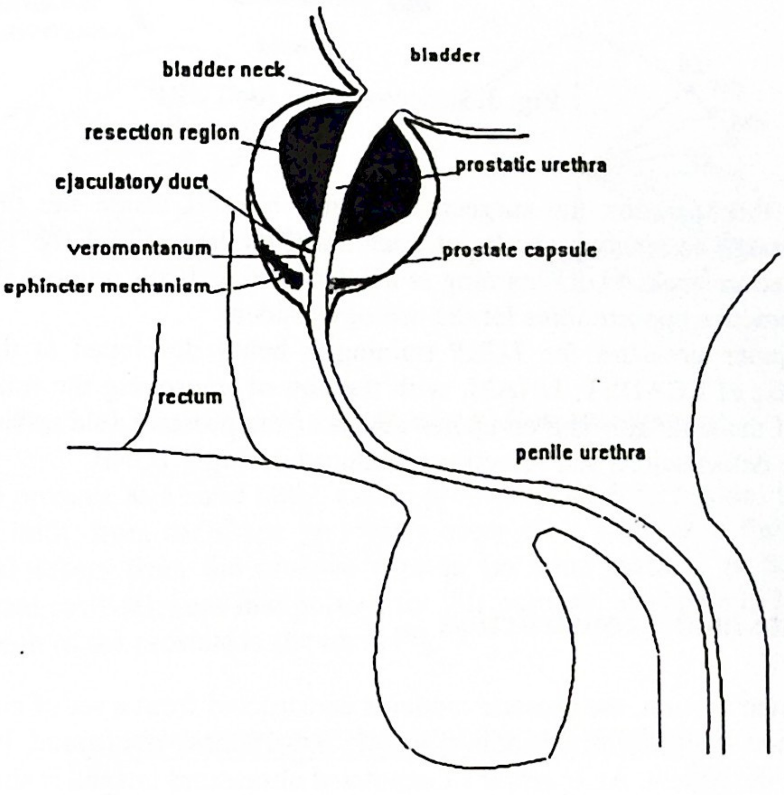

Fig. 2. Anatomy of the prostate

The standard procedure to treat an enlarged prostate gland is the transurethral resection of the prostate in which a surgical instrument called resectoscope (Fig. 3) is inserted through the urethra of the patient. The resectoscope carries in its interior a telescope and a resecting loop that enables the surgeon to remove small chips of prostate tissue.

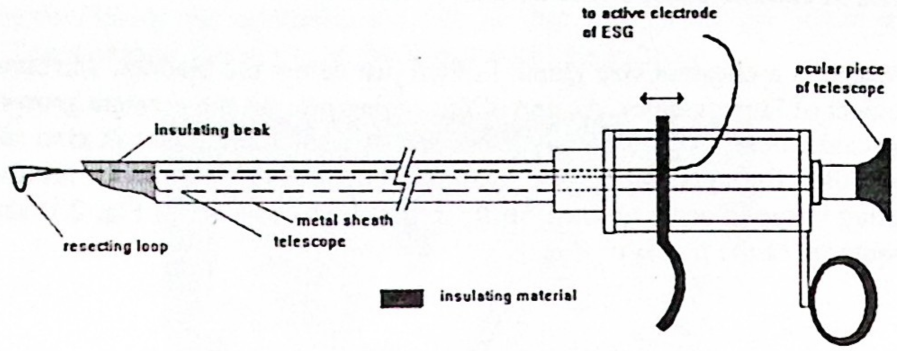

Fig. 3. Resectosocope for TURP

During the operation the surgeon orientates himself inside the prostate of the patient through continuous checks of anatomical landmarks like the *verumontanum* and the bladder neck. TURP training is an slow and difficult process since there are very few practice opportunities for the urology resident.

A computer simulator for TURP training is being developed at the Image and Vision Lab., of CCADET, UNAM, with the aim of improving the training process, the core of the simulator is a computer model of the prostate able to simulate in real time tissue deformations and resections produced during a TURP.

3 Prostate model construction

In our current version, the prostate model is constructed from a set of contours drawn by an expert on the corresponding set of transurethral ultrasound images of the prostate of the patient. An example of annotated ultrasound images is shown in Fig. 4. An automatic alternative for prostate recognition in ultrasound images is being developed at the Image and Vision Lab. [6].

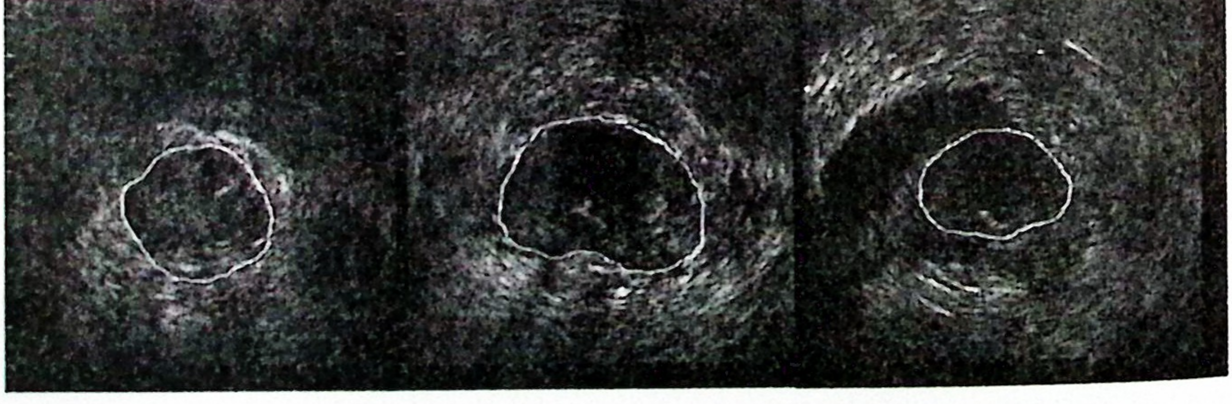

Fig. 4. Annotated ultrasound images of the prostate

Five transversal images were used to construct our current model, each of the prostate contours was radially sampled. New contours were calculated using cubic spline interpolation, a 3D volume of the prostate was build from the whole set (Fig. 5a). Both the angle α in the radial sampling and the number c of points in the cubic spline, interpolation, shown in Fig. 5b, can be adjusted in order to get a 3D mesh with enough visual realism and acceptable time response.

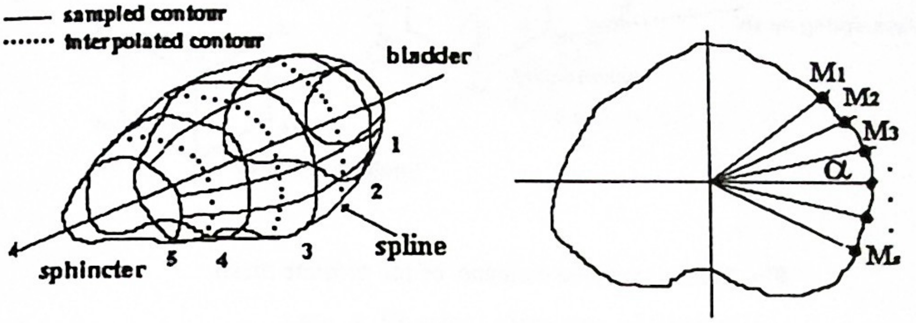

Fig. 5. a) 3D volume of the prostate; b) Contour sampling.

To model the prostate as a solid body, and to propagate the deformations through its structure, we built, from the shape previously obtained, a volumetric finite element mesh. Several layers from the prostate capsule (external surface) to the prostate urethra (internal surface) were interpolated for this purpose, as shown in Fig. 6. The volumetric mesh of the prostate is shown in Fig. 7.

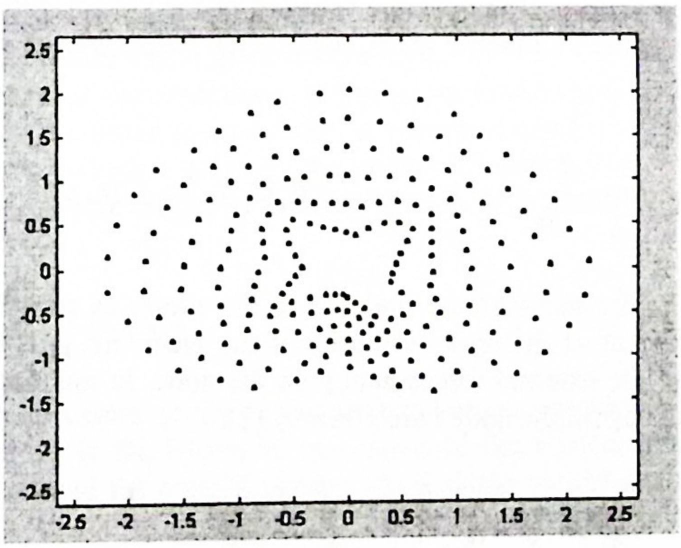

Fig. 6. Inner mesh nodes.

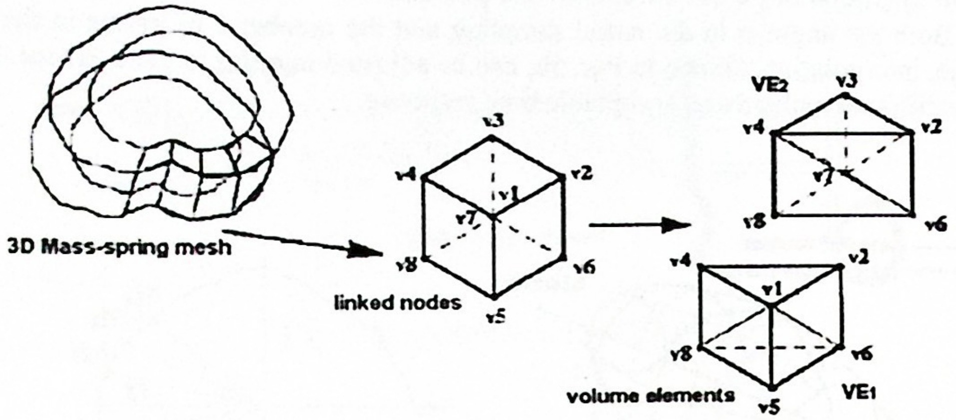

Fig. 7. Final volume elements of the prostate mesh

3.1 Adding physical properties to the prostate mesh

The prostate physical behavior is modeled as a deformable body with physical characteristics like mass, stiffness and damping coefficients. These physical characteristics were adapted to the volumetric 3D mesh constructed before, to produce a viscoelastic 3D mesh. This was done using the spring-mass method [7] (see Fig. 8), which allows us to perform real time deformations. Every node in the mesh represents a mass point that moves in a viscous medium, and is interconnected with its neighbors by springs. The dynamic behavior of the system, formed by the spring-mass elements in the volumetric mesh, is based on the *Lagrange* equation of motion (1).

$$m_i \frac{d^2\mathbf{x}_1}{dt^2} + \gamma_i \frac{d\,\mathbf{x}_1}{dt} + \mathbf{g}_1(t,\mathbf{x}_1) = \mathbf{f}_i(t,\mathbf{x}_1) \qquad (1)$$

Where m_i is the mass of the node N_i in the mesh, at coordinates $\mathbf{x}_i$; γ_i is the damping coefficient of the node (viscosity of the medium); $\mathbf{g}_i$ is the internal elastic force and $\mathbf{f}_i$ are the external forces acting on the node. In this approach the internal elastic forces acting on the node *i* are given by (2).

$$g_i = \sum_{j \in N(i)} \mu_{i,j} \frac{\left(|x_i - x_j| - l^0_{i,j}\right)(x_i - x_j)}{|x_i - x_j|} \qquad (2)$$

Where $\mu_{i,j}$ is the stiffness coefficient of spring connecting node N_i and N_j for all the neighbors in *N(i)* and $l^0_{i,j}$ is the spring length at rest position. In this manner, the deformations occurs as a result of the elastic inner energy change, produced by the spring elongation.

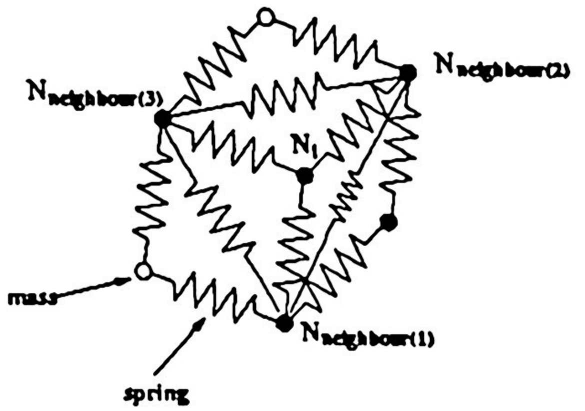

Fig. 8. Physical elements of the mesh

3.2. Tissue Resections and Prostate Deformation

If a collision between the prostate and the resectoscope body is detected, the contact vertex in the mesh is calculated. Then, the geometrical elements (pentahedrons and triangles) and mechanical elements (springs) that surround the vertex are removed from the mesh. Finally the contact vertex is also removed from the mesh. In order to visualize the inner tissue exposed after the resection (after removing the adjacent elements of the contact vertex), the elements corresponding to the tissue exposed are added to the surface mesh, which is the visible layer.

As a consequence of the resections, the prostate model must deform due to the pressure exerted by the tissue surrounding the cutting zone. This pressure acts in (1) as an external force $\mathbf{f}_i$, which is given by the volume variation in the cutting zone. The pressure has been modeled locally in the cutting zone, in a similar way as a hydraulic system (3).

$$\mathbf{p}_i = k_i \mathbf{dV}_i \tag{3}$$

Where $\mathbf{p}_i$ is the pressure acting in the contact vertex, due to the removal of the surrounding tissue; k_i is the hydraulic resistance of the contact vertex; $\mathbf{dV}_i$ is the volume variation around the contact vertex. The volume variation $\mathbf{dV}_i$ is defined by (4).

$$dV_i = c_i \sum_{j \in VA(N_i)} \frac{V_j^c}{V_j^0} \qquad (4)$$

Where V_j^c is the volume of the pentahedron v_j adjacent to the contact vertex N_i ($\forall$ $v_j \in VA$, where VA is the set of pentahedrons adjacent to the contact vertex); V_j^o is the initial volume of all the pentahedrons adjacent to the contact vertex; c_i are the coordinates of the cutting zone center.

4 Results

The model described was implemented in C using the OpenGL libraries for rendering, on a SUN BLADE 2000 workstation (with one processor at 1 Ghz), without specialized graphics hardware. The slides on Fig. 9 show a simulated resection of the prostate model. The figure presents a prostate with an urethra, almost completely obstructed by the tissue that has grown in excess (top left slide) The slides also show the removing process of the adenoma. It can be observed the cavity produced after several tissue resections from the obstructed urethra, and the progressive collapse of the inner tissue.

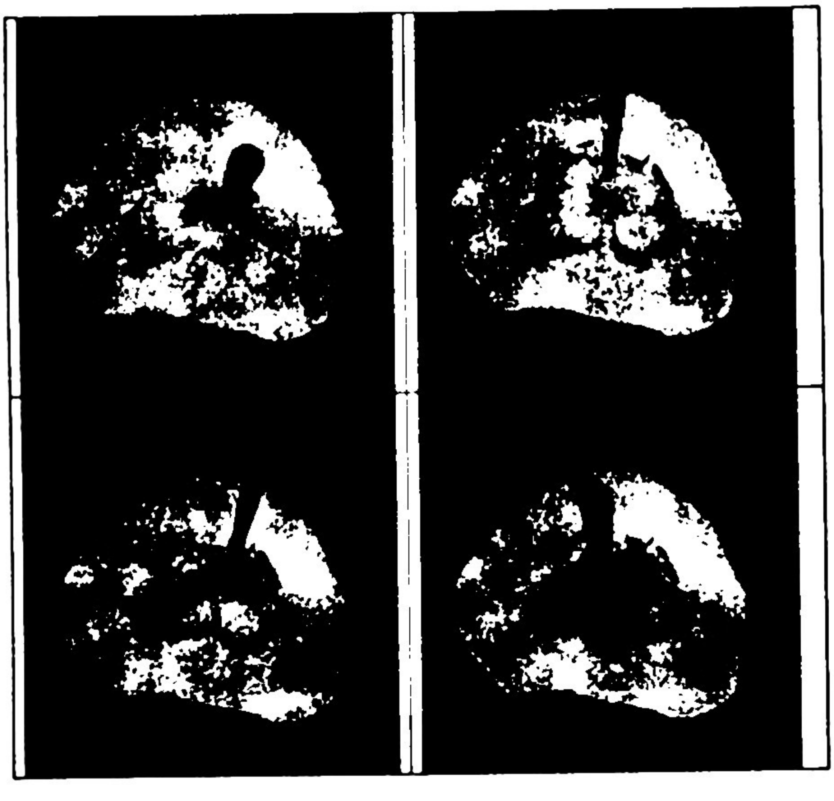

Fig. 8. Resection and deformation of a prostate model with 10800 nodes in its mesh.

5 Conclusion

This paper describes current research at the Image and Vision Lab. of CCADET, UNAM, where we develop automatic image analysis software and 3D models of soft tissue organs for computer assisted surgery training and monitoring.

We have reported a computer model of the prostate that is the basis for the development of a real-time virtual reality simulator for TURP training.. The prostate model is constructed from a set of ultrasound images which can be manually or automatically annotated. A 3D volumetric mesh of the prostate is constructed through sampling of the set of annotated contours. The method allows for control of visual realism of the 3D mesh with appropriate time response, by varying its sampling parameter α (radial sampling angle).

The model is able to reproduce tissue resections of different sizes, depending on the cutting radius of the resectoscope. Along with resections, the model simulates in real-time tissue deformations and the global collapse of the prostate capsule as the resection of the adenoma progresses.

References

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