Motion Planning of Needle For Autonomous Suturing of Wound

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***Abstract*— Recently there have been a lot of advancements in the field of surgical robots. However such robots are mostly teleoperated, some scenarios require the need of automation for precise and accurate procedures. One such application is suturing of a tissue using a circular needle. This project intends to automate suturing, by designing a motion planning algorithm of the suturing needle given an insertion and extraction point specified by the surgeon. The motion of the circular needle is studied and the constraints during suturing are defined. During the course of the project, we propose to use A* and Rapidly exploring random trees for the motion planning of the needle to satisfy the constraints and optimize the path taken. We also propose to use the daVinci surgical robot to demonstrate in simulation the path planning algorithm by calculating its motion for the needle motion. The expected outcome of the project will be a trajectory which plans a motion of the patient side manipulator of the daVinci robot between the two points subjected to certain constraints which minimize the tissue damage.**

I. INTRODUCTION AND BACKGROUND

Robots are currently being used during a lot of surgical procedures in hospitals all around the world. The daVinci surgical system [1] is one such robotic system and the most widely used surgical robot. Most of such system have master and slave consoles. The surgeons operate using the master console and the slaves follows the operation and performs the procedure on the patient. This process is referred to as teleoperation. In this process, the control of the procedure is fully with the surgeon and there is no autonomy on the slave console. However, some procedures can benefit with shared or cooperative control such as during stitching of a tissue.

Most of the surgical procedures involve stitching of tissues. Currently, the surgeons while teleoperating perform trial and error process to reduce tissue damage and deformations. This process can be optimized if the stitching task was automated, albeit the entry point and exit point was given by the surgeon. Moreover this automated procedure would be faster and save surgeon's time. In addition, suturing while teleoperating is difficult due to the limited vision from the endoscopic camera and reduced degree of freedom of the instrument. Hence, algorithms for automated suturing need to be studied and developed. This study aims at precisely this.

Automated suturing has a different set of challenges. The needle used for suturing is a circular needle. This is necessary because if a straight needle were used, it cannot be moved perpendicular to its insertion angle and will travel only in straight line. It need not be possible to suture wounds where only straight line paths for the needle are available. Moreover, there could be a lot of tissue deformation if the needle were to move only in straight line. A circular needle adds complexity to the task of path planning as now the needle has a non-holonomic constraint. For instance, it cannot move in a straight line.

In addition, there is no open source software available for robotics systems which can simulate the dynamics of a deformable body such as a tissue. This makes it difficult to model and accommodate for tissue deformations. Further advancements in such softwares can greatly help in better studies in related fields. Due to lack of simulation environment, we decided to use MATLAB to demonstrate the needle motion and the amount of tissue damage done in the planned path. Some simplifying assumptions were made and have been described in the following sections. For simulating daVinci, daVinci research kit [2] is used. The patient side manipulator is spawned in RViz for visualisation of the task using Robotics Operating system.

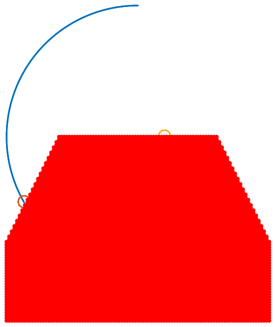
Numerous studies have been done for automating suturing tasks. Jackson et. al [3] has developed two techniques based on best practices of surgeons and minimizing interactive forces between tissue and needles. [4] automates the suturing task with a single arm using the input of a single endoscopic camera. Knot tying, an essential part of suturing, using two arms with the aid of visual servoing has been done by hynes [5]. Studies of Nageotte [6] and Sen [7] describe the task of motion planning for suturing with detailed explanations for the constraints encountered during the suturing procedure and how to model them.

The following section describes the work proposed to be done during the course of this project. Problem statement and algorithms to be used are described in detail. Section 3 describes the experiments that will be done to evaluate our algorithms based on the constraints and cost functions developed. Moreover, the weekly schedule for the project has been tabulated and shown in Table I.

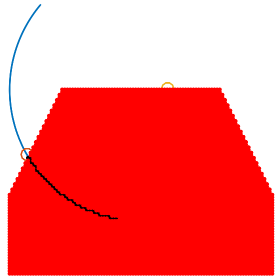
II. PROPOSED WORK

A. Problem Statement

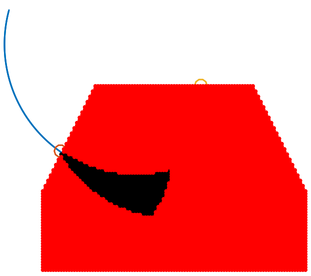
The problem of suturing can be defined in abstract terms as finding a collision free optimal path between two suture points subject to some pre-defined constraints. Mathematically it can be defined as given two suture points p_1 and p_2 and needle function $N(x, y, z)$ should follow a collision free trajectory such that at $t = 0$, $N(x, y, z) = p_1$ and at $t = t_f$, $N(x, y, z) = p_2$ where t_f subject to constraints that at any time t, $N(x, y, z)$ should always belong to the allowed space inside the wound given by Q_{free} out of the total configuration space given by Q. In this case is the time limit for the algorithm generalizing for both deterministically and probabilistic complete motion planning algorithms.



(a) Fig : 1a



(b) Fig : 1b



(c) Fig : 1c

Fig. 1

As a prerequisite, it is necessary to model the transition function for the needle as a function of inputs. In this case, we assume three inputs namely, Insertion (δx), Twist in the plane of needle (α) and Twist in the plane perpendicular to the plane of needle (β). This transition function will eventually give the pose of the complete needle body in 3D space. Additionally we will design a custom simulator in MATLAB for visualizing the progress of the algorithm and also for presentation purposes as shown in Fig[1(a)].

The above search problem is made more complex by adding constraints which are necessary for recreating human-like expertise in suturing operations. The constraints can be enumerated as follows :

1) Minimize Tissue Damage: For real suturing operations, surgeons often aim to minimize tissue damage to reduce internal bleeding thus avoiding further complications during surgery. Needle motion during autonomous suturing must also include this attribute. Generally, tissue damage is caused by motions in all degree of freedom. Motion along the curvature, causes tissue damage by piercing through the tissue along the same curvature as shown in Fig[1(b)]. Motion involving rotation of needle about its insertion point in any plane, ruptures the tissue sideways thus causing more damage as shown in Fig[1(c)]. The aim of the proposed motion planning algorithm is to minimize the cumulative tissue damage caused by the two types of motions. To simulate and calculate the damage for this project, we consider the damage done by needle insertion action as cross-sectional area corresponding to needle tip and the insertion step length. For twist motion, the damage will be calculated as the area of the sector swept when rotating the needle by an angle γ about the insertion point.

2) Minimize Needle Travel inside the tissue: This constraint is essential as it can be intuitively seen that from the above constraint, insertion motion (along the curvature) will be favored more compared to twist motion. This will result in longer trajectories which are often not prescribed during medical suturing. In the case for this simulation based project, we simulate the length of trajectory by the total distance traveled by the tip of the needle.

3) Normal Bite of the Needle: It is essential for the needle's insertion angle to be as close to the normal to the wound surface at insertion point. This guarantees insertion with minimum force which again translates to minimum effort required by the manipulator which controls the needle. Likewise,during extraction it is essential for the condition to be satisfied. This constraint also relates to minimizing damage at the entry point.

4) Avoid Restricted areas: During suturing it is a best practice to avoid thick tissue or bone material. We define these areas with gray-zones (Q_{obs}) where $Q_{free} \cap Q_{obs} = \phi$

B. Algorithm

As this motion planning problem proposes to minimize constraints and find an optimal plan, we propose to use the A^* algorithm with specially designed cost function and heuristic so as to guarantee a collision-free and optimal path. This resonates with various constraints stated above.

The cost for each edge in the planning graph is derived from the individual constraints. This cost can be visualized as a sum of the area of tissue damage and the needle traversal. In case of insertion action the tissue damage will be minimum but the traversal cost will dominate on the other hand during twist action, the tissue damage will dominate. Mathematically of an edge between two nodes X and Y can be written as follows :

$$cost(X, Y) = A(X, Y) + l(X, Y)$$

where $A(x, y)$ is the area of tissue rupture and $l(x, y)$ is length of needle traversal.

We propose the heuristic to be used as the euclidean distance of the needle tip from current position to the desired goal position. This heuristic can be proved to be admissible and consistent by the fact that it gives the minimum distance to the goal as the motion of the needle is non-holonomic.

A* algorithm though optimal, may not be feasible as the dimensionality of action space is large. This will result in longer run-time but less feasible to use in real time systems. Thus we also propose to use Rapidly Exploring Random tree (RRTs) to get a feasible path although non optimal. The advantage of RRT is that it randomly samples points in the configuration space thus being fast but probabilistic complete. In this particular motion planning problem, RRT might also have some limitations as the configuration space is similar to that of *bug trap*.

III. PROPOSED EXPERIMENTS AND EXPECTED OUTCOMES

The algorithm will be tested in the proposed MATLAB environment. Our custom-built environment allows us to simulate different conditions for wound and tissue structure. This enables us to perform experiments on various test cases/conditions, some of which are as follows :

1) Extension to 3D Workspace: The algorithm with the given environment will be tested in 3D workspace i.e insertion and extraction points belonging to different planes. It is expected that given the degrees of freedom for the needle, the algorithm will converge to global goal given the extraction point is physically possible to reach. Thus there will always be an solution for A*. If a solution is found with RRT it is expected that its run-time will be less that A*.

2) Narrowing the obstacle free path: Narrowing the obstacle free path will involve traversing through highly constrained configuration space. In this case it is expected that A* algorithm will outrun RRT as probability of sampling nodes in a narrow passage is less likely.

IV. WEEKLY SCHEDULE

In this section, we discuss the weekly schedule for our project. It is represented in Table I

TABLE I: Description of tasks to be completed during the project and their schedule

Week	Tasks
Week 1	Calculating transformations of needle and setting up simulation environment
Week 2	Modelling constraints and cost functions
Week 3	Motion planning of the needle using A*
Week 4	Motion planning of the needle using RRT*
Week 5	Developing trajectory of the patient side manipulator of daVinci for the planned motion
Week 6	Compiling results of the experiment and writing report

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