# Towards robot guided waterjet surgery

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#### Abstract:

Papachristou and Bartes [1] first used a waterjet in the medical context. By using a waterjet in ablative liver surgery intrahepatic parenchyma could be washed away whereas vessels and ducts stay undamaged and intact which leads to less interoperative loss of blood. The aspect of tissue selectivity is one of the major advantages of using a waterjet to prepare soft tissue. This work first explains the physical basics of this method and differs between relevant properties which are responsible for the cutting effect. From that, the method of handling a waterjet applicator is derived. Furthermore, the restrictions of handling a waterjet applicator in laparoscopic surgery are shown and a robot supported solution for this problem is suggested. Finally, first experiments of the robotic solution using gelatin samples are presented and discussed.

Keywords: Waterjet Surgery, Medical Robotics, Minimally Invasive Robotic Surgery

#### 1 Problem Statement

Waterjet surgery uses a thin and high pressure jet to prepare soft tissue. The cutting effect depends mainly on the velocity of the jet which is proportional to the pressure and the characteristics of the soft tissue to be prepared [2, 3]. The soft tissue characteristics are patient specific. Therefore, the cutting effect is adjustable by varying the pressure of the jet. If the jet hits the tissue cutting is a result of either the impact pressure or the stagnation pressure [2]. The impact pressure is more effective but has to be maintained by the common oscillating movement of the waterjet applicator. In minimally invasive surgery this method is limited due to kinematic constraints at the fulcrum. By the use of robotics these restrictions can be overcome and the full applicability of the waterjet surgery can be restored.

# 2 Materials and Methods

Using a waterjet to prepare soft tissue was announced first by Papachristou and Bartes in 1982 [1]. A conventional agricultural sprayer in combination with saline, a special nozzle, and a pressure regulator were used to perform an intrahepatic dissection in ablative liver surgery. 45 lobectomies on dogs and 4 liver resections on humans were reported showing the selectiveness of this preparation method. Parenchyma tissue can be washed away whereas vessels stay intact. This effect depends on the mechanical characteristics of the material. Each tissue has a specific mechanical resistance against the effect of the jet which corresponds to a specific pressure. As long as there is a clear difference in the resistance of two materials the pressure of the jet can be adjusted to wash away one material whereas the other one stays intact. These effects are also verified by other works, e.g. [4, 5]. The waterjet technique can meanwhile be regarded as established and is also used in other surgical application fields e.g. neurosurgery, orthopedics, and otolaryngology [6, 7, 8, 9, 10].

The physical basics of the waterjet technique are understood in mechanical engineering, where it is used for material processing. According to [2] with the assumption of an adequate plunger pump the nozzle diameter does not affect the velocity of the jet. Due to this, the velocity of the jet depends only on the system pressure. In good first approximation, Bernoulli's equation for incompressible fluids is applicable [2]:

$$v = \sqrt{2\frac{P}{d}}$$

$$v = velocity$$

$$P = pressure$$

$$d = fluid density$$

Hence, the cutting effect can be adjusted by varying the pressure. The geometry of the jet changes with increasing distance to the nozzle [3]. Directly at the nozzle the jet consist of a single liquid volume. With increasing distance the compact jet gradually turns into an accumulation of drops. Therefore, the best cutting effect can be achieved in the distance of a few centimeters to the nozzle [2].

Two different influences are responsible for the cutting [3]: the impact pressure and the stagnation pressure. The impact pressure (see left side of Fig. 1) is effective when the jet first hits the material. It only lasts for a few microseconds but has a very high impact during this phase. Afterwards, radial flow is formed around the target of the jet. This phase is called the stagnation pressure (see left side of Fig. 1) and the impact decreases significantly.



Figure. 1: Cutting effects, impact pressure (left side) and stagnation pressure (right side)

Assuming the depicted physical behavior of the jet can be transferred to soft tissue the common method of handling a waterjet applicator in surgery (Fig. 2) is comprehensible. By performing an oscillating movement tangential to the dissection trajectory the impact pressure can be maintained. This method can easily be performed in open surgery. However, in minimally invasive surgery the use of this method is limited. In minimally invasive surgery two degrees of freedom (DOF) are bound at the fulcrum. Using an applicator without additional DOF every position at the tissue can only be reached in one orientation (see left side of Fig. 3). By the use of robotics additional DOF can be integrated and every location is reachable in different orientations (see right side of Fig. 3) within the valid workspace of the robotic system. The actuation of the applicator inside the body overcomes the kinematic restrictions of minimally invasive surgery. Additionally, the tangential oscillation can be implemented as a semi-autonomous functionality supporting the surgeon. This approach enables the use of the waterjet technique in other interventions in which this technique is not applicable so far.



Figure 2: Oscillation along trajectory

Figure 3: Reachable applicator orientation

The common oscillation method of handling a water jet applicator was ported to a robotic system comprising the DLR MIRO robot [11, 12] and the DLR MIRO instrument [13]. In the experiments the ERBEJET® 2 and its associated flexible probe is used. By coupling the nozzle of the flexible probe to the end effector of the DLR MIRO the full manipulability can be restored. The waterjet can be handled in the manner known from open surgery. Furthermore, the exhaust-

ing task of generating an oscillation is carried out by the robotic system. The surgeon only commands the desired dissection trajectory and oscillation amplitude. The tangential orientation is derived from the desired trajectory and the oscillation is performed by the robotic system. As the desired frequency of the oscillating movement is in the range of 3-6Hz (derived from manual oscillation), the entire robot would move at this frequency outside of the patient. This is avoided by adapting the oscillation to some kinematic constraints of the robotic system. The oscillation is only applied to the universal joint of the DLR MICA. Hence, only the low mass of the end effector and nozzle has to be accelerated to perform the oscillating movement. Hence, the DLR MIRO robot only follows the movement related to the commanded trajectory.

For in vitro tests ballistic gelatin (GELITA® GELATIN Type Ballistic 3) is used. Ballistic gelatin is characterized by its good comparability to human tissue concerning waterjet dissection. Its mechanical characteristics are adjustable by the mixing ratio. Furthermore, the good transmission factor is suitable for visualization of the performed trajectories.

# 3 Results

As experimental trajectories a square and a circle are used. The square is suitable to show the behavior of the implemented method in case of an abrupt change in the direction of the trajectory. The circle shows the tangential approximation of the trajectory quite well. Both are simulated user trajectories, generated by a trajectory generator.

The water pressure is adapted to the number of repetitions of the trajectory, the velocity along the trajectory and the mixing ratio of the gelatin samples. Every trajectory is repeated five times at a velocity of 0.015m/s. By using a mixing ratio of 93:7 (water : gelatin) and a jet pressure of 55-60bar a good cutting effect can be achieved without full penetration of the gelatin samples. In the experimental setup the trocar position is 120mm away from the end effector at the shaft of the instrument. The distance between the waterjet nozzle and the gelatin sample is 10mm.



Figure 4: Circle trajectory



Figure 5: Square trajectory

The resulting ablation of the test trajectories is shown in Fig. 4 and Fig. 5. For both the commanded amplitude of the oscillation is 3mm at a frequency of 4Hz. The radius of the circle trajectory is 9.5mm. The length of a square side is 20mm.

# 4 Discussion

The experiments show that the implemented method is able to follow an arbitrary trajectory. The mathematical function describing the transection geometry has definite mapping characteristics. Hence, the achievable repeatability is determined by the robotic system. As the algorithm only affects the tip of the instrument a very low mass needs to be accelerated. This greatly reduces the effect of disturbances (e.g. vibrations) to the repeatability and accuracy. The thin and exact course of both trajectories after five repetitions shows that the repeatability is well suited for the application. The tangential approximation to the commanded trajectory can be investigated by the circle trajectory (Fig. 4). The commanded circle is clearly approximated by a polygon. The frayed shape is a result of the amplitude of the oscillation. It is willfully chosen bigger to visualize the tangential approximation. In case of a manually commanded trajectory the amplitude of the oscillation is adjusted by the user to achieve the desired ablation rate and accuracy. The square trajectory (Fig. 5) shows that the implemented method is also able to react to abrupt changes in the direction which can be recognized at the accurate corners. The slight overshoot in the forward direction is a result of the synthetic trajectory as the amplitude of the oscillation is constant along the commanded trajectory. This behavior is not relevant in case of a manually commanded trajectory as the amplitude of the oscillation are that the user has knowledge about the course of the trajectory the amplitude of the oscillation are adjusted accordingly.

# 5 Conclusions

The common method in handling a waterjet can be adapted to constraints of minimally invasive surgery. The surgeon only has to command a virtually non-oscillating instrument. Nevertheless, the end effector oscillates. The zero crossing of the modulated oscillation is the virtual instrument tip. This poses an additional challenge to the surgeon. In spite of the promising results of the first experiments further tests are necessary especially with a human in the loop. The usability has to be checked concerning the control of the oscillation as well as the handling of an oscillating end effector. Besides, additional surgical applications to liver tissue resection have to be identified which can profit of this improvement in handling a waterjet applicator in minimally invasive interventions. At the present state, this technology appears to have the potential to be applicable in robot supported surgery and, therefore, to open up new possibilities.

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