Part 1: Path Planning Algorithms

There are many path planning algorithms that can be utilized to control the movement of a robot. Of these algorithms, I will be focusing on three algorithms built-in to the Robotics Toolbox for MATLAB developed by Peter I. Corke which are the Distance Transform, D Star (D\*), and Probabilistic Road Map (PRM) methods.

The Distance Transform method is the simplest and takes in a map, start, and end locations to compute the distance of every square to the goal and chooses the path with the least distance. Although producing the most linear and clean results, this method only works practically with small obstacle maps. Since the method has to compute every possible path from every available square in the map, the computational power required to find the same path increases exponentially when increasing the dimensions of the map.

To implement this path planning algorithm, first an obstacle map matching the clipboard where the robot is mounted must be made. In order to make this map, I set hardcoded values for the size and position of the tic-tac-toe grid so the location of the grid and center points of each outside cell is always known, and created a map the same size as the clipboard. Then, I can create obstacles using the “map( )” command matching the shape of the grid. Also, I created the obstacles to be 4mm thick to account for the thickness of the lines drawn by the marker. This will be apparent when the algorithm is drawing the path and the path will always be a minimum of 2mm away from the grid. I decided on a starting point somewhere above the grid and I collected the center points of each outside grid cell to be goal points. The algorithm cannot process multiple goal points at once, so I used a for loop to call the algorithm to find the path for each goal point individually, set the previous goal point as the new starting location, and concatenate each generated path to form a chain of paths. In effect, a path is drawn clockwise around the grid that starts from a point above the grid and jumps to the next cell over until a full revolution is completed. This method was by far the fastest with a time of 0.206 seconds considering the relatively small size of the map. The result of this method is shown in Figure 1.

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| Chart  Description automatically generated |
| Figure 1: Result of Distance Transform method |

To avoid the high cost of using the Distance Transform with larger occupancy grids, roadmap methods, such as the D\* and PRM algorithms, are developed. The D\* method is an extension of the A\* method which utilizes traversable points known as nodes and generates a cost map. Each node has a calculable weight that defines how much work is needed to go from one point to another. A path is developed that finds the lowest cost between points which is effectively the most optimal path. The advantage of D\* over the Distance Transform is that the D\* algorithm is capable of cost effective, incremental re-planning when facing a high than normal cost as opposed to the Distance Transform algorithm which has to completely re-plan a path once it proves to be inefficient.

Implementing the D\* algorithm was extremely simple, as all the code used in the Distance Transform method was copied and pasted. The only change made was switching the class used from “DXform” to “Dstar” and some variable name changes. Unfortunately, this method by far was the slowest method and took a whopping 22.651 seconds to calculate the path around the grid. However, the smoothness is very comparable to the Distance Transform method as demonstrated by Figure 2.

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| Figure 2: Result of D\* method |

Finally, The PRM method approaches a roadmap by randomly plotting nodes in the map and determining a path from connecting these random nodes to the goal point node. There are several advantages and disadvantages to this method. The path generated is jagged as the paths are randomly generated and even has a chance of not being able to converge on a path as shown in Figure 3. Furthermore, the obstacle map had to be greatly changed in order to get something that even resembles a path. The map was shrunk from the entire clipboard to just the section of the clipboard that the grid was drawn in. Also, massive obstacles had to be introduced to further eliminate free space so the randomly placed nodes would be much closer to the grid. Without taking these steps, the generated path would look like scribbling on the clipboard. However, the calculation time was greatly reduced compared to the D\* algorithm with a time of 3.594 seconds, and even the drawing process was speedy as well.

Some changes had to be made to the code in order to implement the PRM method. As stated above, the obstacle map was greatly reduced to only include the grid so nodes could be condensed around the grid. Then, the “.plan( )” property was changed into a function with no arguments and the “.query( )” property now required both the start and goal XY coordinates instead of just the start coordinates. Other than these changes stated above, the rest of the code was extremely similar to the previous path planning algorithms in terms of implementation.

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| Figure 3: Result of PRM method |

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| Figure 4: Comparing all the path planning methods together |

As shown in Figure 4, the processing time varies greatly with each method. Across the board, the size of the obstacle map had a proportional effect on the processing time. Each algorithm has their own place and time to be used. For the purposes of our small-scale robotics project, the Distance Transform method is far and away the best path planning method with our small workspace and lenient capacity for errors. I believe this method works well for small, stable projects and demonstration purposes. The D\* method is great for actively changing environments, such as a hospital, as it has the ability to re-plan in real time instead of the total re-planning of the Distance Transform method. Finally, the PRM method is similar to the D\* method and can be used in the same environments but with quicker and clumsier movements.

Part 2a: Medical Robotics

The implementation of da Vinci Surgical Systems has greatly changed the medical world and is on track to continue doing so. Minimally Invasive Surgery (MIS) has now become much more viable over recent years with the introduction of precise robotic instrumentation in surgeries. This is known as Robotic Minimally Invasive Surgery or RMIS. Robotics has proven to be the greatest advancement in surgery over the last decade. It brought about wide access to doctors for surgery with the decoupling of the surgeon from the operating table and many other new breakthroughs. However, access to da Vinci surgical systems for research use was limited as there were a limited supply of these systems and most of them were already in use for clinical applications while recording kinematic data that was only available with a collaboration agreement with ISI (Intuitive Surgical Inc.), the manufacturers of da Vinci surgical systems. The dVRK research platform was founded in a collaboration between Johns Hopkins University, Worcester Polytechnic Institute, and ISI to allow researchers access to the da Vinic surgical system. Researchers were given decommissioned, first-generation da Vinci surgical systems and their necessary electronics to allow complete access and control to every aspect of the robot. These repurposed systems are known as dVRKs. Ever since the proliferation of dVRKs, peer-reviewed research articles flourished with more than 25,000 peer-reviewed articles to date. The dVRKs and RAVEN robots are the only examples of open research platforms in surgical robotics that have been used across several research groups. The authors aim to provide a comprehensive overview of the research carried out to date with dVRKs. It is to quickly brief readers about the current research going on and the developments made using dVRKs. They want to show the success of the dVRK research platform and set a precedent for future research initiatives.

Not all publications were reviewed out of the 25,000. Of those publications, only those published in international conferences or journals were selected, going down from 25,000 to 253. Papers were further broken down into research fields of generally six categories: 1) Automation, 2) Training, Skill Assessment, and Gesture Recognition, 3) Hardware Implementation and Integration, 4) System Simulation and Modeling, 5) Imaging and Vision, and 6) Reviews. These six research fields form the bulk of the article. Another categorization of these publications was based on which of the five dVRK-generated data types were being researched.

Automation is one of the research fields most popular among researchers as it could drastically change the medical world. Some minor automation has been achieved, such as tremor reduction, but the dream is having a fully automated surgery through the advancement of robot design and control, and machine learning algorithms. Since there are multiple ways to automate surgical tasks, the authors split research in automation into 3 sections: general control, instrument control, and camera control.

Research into general control focuses on control architectures developed for automation in RMIS (Robotic Minimally Invasive Surgery). Publications have explored human-robot interactions, general motion compensation when working in live environments, and control in unknown environments. When considering instrument control, six surgical tasks seem to be most researched: 1) Suturing, 2) Pick, Transfer, and Place, 3) Cutting and Debridement, 4) Retraction and Dissection of Tissues, 5) Blood Suction, and 6) Tissue Palpation. For camera control, although there are functional and approved automated camera control systems, they have not been widely adopted by the surgeons. These systems were built on data-driven path planning while the newer systems are built using machine-learning approaches from veteran doctors in an effort to satisfy the surgeon’s needs.

Training, Skill Assessment, and Gesture Recognition research is used to develop algorithms that can infer surgical processes from the user or train green surgeons and AI. All surgical equipment requires substantial user training in order to be used correctly, but this is more easily achieved through the dVRK which can replay entire recorded surgeries performed by expert surgeons. Furthermore, these surgeries can be used as data to train machine-learning algorithms to become expert surgeons themselves. Several training environments have been researched to find the ideal conditions for teaching novice surgeons or fresh AI such as dry labs, simulations, and recordings. Haptic feedback has also been developed in order to more closely replicate the surgery and further immerse the teleoperator. When training future surgeons, studies have delved into analyzing the skill of the user through proficiency tests and how the user could handle the mental and physical workload with or without haptic feedback. Using trained AI, the dVRK could also analyze and recommend a procedure for the surgeon to follow should they require assistance from a second party.

The Hardware Implementation and Integration field focuses more on the physical operation of the dVRK through software and hardware advancements. Examples of such advancements would be gravity compensation, haptic feedback, on-screen Heads-Up Display, unique surgical tools, virtual reality headsets or augmented reality interfaces, ergonomics of the user interface, overall optimization of the of the time-delay between surgeon and robot and positioning systems, and more. Generally, anything that affects the manual operation of the device was put under this research field.

Although a smaller section compared to other research fields, System Simulation and Modeling is a widely researched topic and was only shortened due to the authors’ approach to selecting publications. Simulation plays an essential role in training and preparing old or new surgeons to perform surgical tasks and to help automate future surgeries. Many aspects of surgery can be simulated such as the force of soft or hard objects, the precise kinematic and dynamic properties of the dVRK, high-intensity environments, etc. There is much potential to be researched in this field as current simulators aren’t nearly as immersive as they could be.

The Imaging and Vision research field is mainly about the user display, camera positioning, and image processing for AI recognition. Optimizing hand-eye calibration has been researched in detail due to its importance in connecting the teleoperator to the operating table. Much information can be extracted from processing the camera output and relayed to the user by employing algorithms that can detect key elements during the surgery to avoid mistakes, advise the user, and perform automatic tasks. There have been many advancements in vision technology where the display has completely been changed such as augmented or virtual reality, ultrasound, and photoacoustic imaging, and other advancements which automate the positioning of the camera for easier usability and patient safety. The data that can be collected from these camera systems is immense and can hopefully be utilized to develop more proficient algorithms.

The last field of research, Reviews, is more about the validity of the advancements achieved by dVRKs and how it is peer-reviewed by major review publications. dVRKs are recognized as state-of-the-art research platforms and spark discussions about legal implications and analyze the future of these research projects and where it will lead the medical world.

In summary, the authors provided several areas of research after filtering out only the most widely accepted publications. Each of the six areas of research were briefly discussed and highlighted many of the latest and greatest advancements in each area. Moreover, citations to every topic discussed were indicated with a number related to the references section at the end of the article should the reader decide to further inquire about an interesting subject.

Part 2b: Medical Robotics

Source: [263] G. Z. Yang et al., “Medical robotics—Regulatory, ethical, and legal considerations for increasing levels of autonomy,” Sci. Robot., vol. 2, no. 4, p. 8638, 2017. doi:10.1126/scirobotics.aam8638.

Link: [Medical robotics—Regulatory, ethical, and legal considerations for increasing levels of autonomy (science.org)](https://www.science.org/doi/pdf/10.1126/scirobotics.aam8638)

This article implores the reader to think critically about the possible future and influence robotics could have. Things that were once only science fiction are slowly but surely coming to fruition with the rapid advancement in robotics, machine learning algorithms, complex control systems, and so much more. Currently, robotics has already dived deep into medical territory and established itself as a viable option. However, the further robotics advances, the more regulations must be put in place to avoid catastrophic tragedies from negligence or malpractice. People are already hesitant about autonomous robots as it is due to the fear of machines going rogue, and any small mistake can affect the public’s view on autonomous machines administering medical aid. That’s why intense regulation is required to keep these robots safe for the public. But this comes with the cost of drastically reducing the speed at which these machines can be manufactured while the development of these robots will not be slowed.

Regulations are necessary for something with the potential to change life as we know it, so the article introduces six levels of autonomy for surgical robots that gradually increase in regulation just like there are for autonomous vehicles. The higher the level of autonomy, the more regulation that needs to be introduced to keep the system secure. Level 0 describes a robot with no autonomous function. It is completely reliant on the teleoperator and will not make a move without some outside influence.

Level 1 autonomy is described as robot assistance. This level of autonomy is only meant to analyze the situation and present what it thinks it currently the case to the surgeon. An example of this would be using image data from a camera and detect which organs are affected, or what course of action should be taken, or an augmented reality interface that overlays a model of some growth to be extracted, etc. There could also be some slight mechanical assistance such as tremor-resistance which only helps the operator make careful movements. As you can expect, some regulatory measures are in order, but with the minimal amount of autonomy, such measures will be slight and concise.

Level 2 autonomy is described as task autonomy. The robot may engage in a simple task such as suturing only with the confirmation and attentive supervision of the teleoperator. This is different from level 1 autonomy because now the surgeon has left the controls to the robot and is only observing for mistakes. Regulations at this level will be apparent and will need to be considered as there is now short amounts of time where the teleoperator will not be in control.

Level 3 autonomy is described as conditional autonomy. This level of autonomy can analyze, strategize, and with the help and permission of the teleoperator, perform multiple tasks without close supervision. This device can also detect potential wearer movement and correct itself without the need for actual intervention. It seems to me that at this level is when the regulations start to get really strict and cause slowdowns in manufacturing due to the amount of risk involved in having a robot sense, decide, and perform various surgical tasks, even with human supervision. This seems like a development where malpractice, negligence, and cybersecurity attacks could easily take place.

Level 4 autonomy is described as high autonomy. This is where we start to delve into the realm of science fiction as the technology is so far beyond what we have today, it might take a lifetime to reach this stage. High autonomy is when the robot can make medical decisions self-reliantly but under the oversight of a qualified doctor. The article describes this kind of robot as more of a “robotic resident” that performs surgery under supervision just like an upcoming doctor completing their residency in a hospital.

Finally, we get to the last level of autonomy that we only see in movies and hopefully aim to achieve someday. Level 5 autonomy is described as Full autonomy. The robot is considered a capable and reliable surgeon/doctor that is capable of all procedure performed by general surgeons. There is no outside human interaction between the robot and the patient. Since the robot is considered to be a valid surgeon, it will also have to pass the tests required by actual surgeons should it boast such a claim. A device such as this is so unfathomably complex in today’s day and age that we can only dream of reaching this stage at some point in the future. And just as the device is unfathomably complex, so will be the laws and regulations adopted to keep a masterpiece such as this safe for use.

The higher we get in autonomy the more we have to consider the implications of having such machines incorporated into the daily lives of billions of human beings. The incredible skill and attention required for surgeons and doctors today will diminish the more and more machines can automate tasks. Roles of medical specialists will shift from being masterfully skillful and experienced to analyzing situations and determining courses of action. So, the trade off in having these amazing machines help save more lives than ever is that the skill of today’s medical staff will further and further diminish the farther down along the line we go.

In summary, the article asks the reader to consider how advanced medical devices should be regulated when considering the practically limitless situations and risk these devices will be placed in. We have to somehow breakdown the different levels of autonomy such that the corresponding regulation can be passed to keep these machines safe and accessible.