Proceedings of the 2018 Design of Medical Devices Conference
DMD2018
April 9-12, 2018, Minneapolis, MN, USA

DMD2018-6840

PORT PLACEMENT OPTIMIZATION FOR ROBOTICALLY-ASSISTED MINIMALLY INVASIVE SURGERY

Robert G. Stricko III
Intuitive Surgical Operations, Inc.
Sunnyvale, CA, USA

Brett Page
Intuitive Surgical Operations, Inc.
Sunnyvale, CA, USA

Amy E. Kerdok
Intuitive Surgical Operations, Inc.
Sunnyvale, CA, USA

Brandon Itkowitz
Intuitive Surgical Operations, Inc.
Sunnyvale, CA, USA

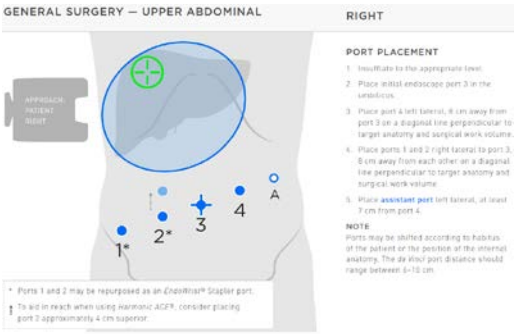
Jason Pile
Intuitive Surgical Operations, Inc.
Sunnyvale, CA, USA

BACKGROUND

Minimally invasive surgery (MIS) requires ports to be placed through the body wall in a manner such that instruments can reach a desired area. Limitations of laparoscopic surgery include maintaining triangulation and ergonomics for the surgeon while allowing access to the anatomy with non-wristed instruments [1]. In robotically-assisted MIS, the surgeon does not stand bedside, and they have wristed instruments that the robot manipulates. Limitations of robotically-assisted MIS include range of motion (ROM) limits and decreased spatial awareness, resulting in the potential for interfering robotic components. As a result, port placement varies between laparoscopic and robotically-assisted surgery.

Port placement is a critical step for robotically-assisted MIS setup, and, if executed poorly, it will result in a number of difficulties throughout the procedure. These difficulties include, but are not limited to, instrument reach issues due to ROM limits, spar interferences, and unnaturalness of instrumentation due to their position relative to the scope's field of view (FOV). The spar is the most distal link of the patient side cart (PSC) that attaches to the cannula, controlling the insertion axis of the instrument. Naturalness will also be referred to as "anthropomorphicness" as it is related to the human's perception of where one's hands should be relative to one's eyes.

Clinical specialty guides (shown in figure 1) are developed by the manufacturer (Intuitive Surgical) empirically with surgeon input, and are validated in cadaveric models [2]. These clinical specialty guides, in combination with personal and peer experience, are used to inform the surgeon's port placement. A "one size fits all" port placement strategy is adequate in theory, however, in practice, optimization to patient's specific needs (i.e. patient habitus) is lacking. The goal of this research was to provide more objective port placement suggestions by approaching the problem through more analytical patient-centric methods.



PORT PLACEMENT

1. Insufflate to the appropriate level.
2. Place initial endoscope port 3 in the umbilicus.
3. Place port 4 left lateral, 8 cm away from port 3 on a diagonal line perpendicular to target anatomy and surgical work volume.
4. Place ports 1 and 2 right lateral to port 3, 8 cm away from each other on a diagonal line perpendicular to target anatomy and surgical work volume.
5. Place assistant port left lateral, at least 7 cm from port 4.

NOTE
Ports may be shifted according to habitus of the patient or the position of the internal anatomy. The da Vinci port distance should range between 6-10 cm.

* Ports 1 and 2 may be repurposed as an EndoWrist® Stapler port.
To aid in reach when using Harmonic ACE®, consider placing port 2 approximately 4 cm superior.

Figure 1: Example port placement recommendations from da Vinci Xi clinical specialty guide

METHODS

General approach

The goal of this project was to optimize port placement across reach, spar interference, and anthropomorphicness. The challenge is that these criteria are functions of port placement and one another. For example, instrument reach is related to the robot's ROM limits and the location of its port. Consequently, the robot's port location that allows for sufficient reach also affects the position of that instrument's spar, which affects spar interferences. To optimize across all of these criteria, each criterion is graded on an independent metric. By grading each criterion independently, a weighted score may be found for a set of port locations. By iterating across the body wall, grading a sample of possible port location sets, a maximum score can be found and the optimal port locations may be returned to the user.

Development of Scoring Criteria

Instrument Reach

Reach was the first criterion that was developed, and it refers to having the surgical workspace lie within the bounds of the instrument's ROM. To do this, several variables must be defined, including the location and size of the surgical workspace and the ROM of the instruments. For the example procedure, cholecystectomy, the workspace was centered on the gallbladder and the surgical workspace was defined as an ellipsoid of sufficient size for the patient's body. Based on the robot architecture of the da Vinci Xi, the ROM of each instrument was defined as a cone of reach, in an orientation that is standard for a cholecystectomy.

By performing nonrandom 3D sampling, geometric equations can be applied to see every point that exists in the volume of the ROM for a given port placement. Based on the surgical workspace inputs, these points can also be checked for whether they exist within the volume of the surgical workspace. If every point within the surgical workspace also lies within the ROM, then the instrument is said to have full reach of the surgical workspace. This analysis is run for two instruments, right and left hands, to ensure that the surgeon has full access to the surgical workspace with both instruments (shown in figure 2). This criterion is scored as a pass/fail metric because if an instrument cannot access its workspace, the surgeon will not be able to proceed until an additional port is placed.

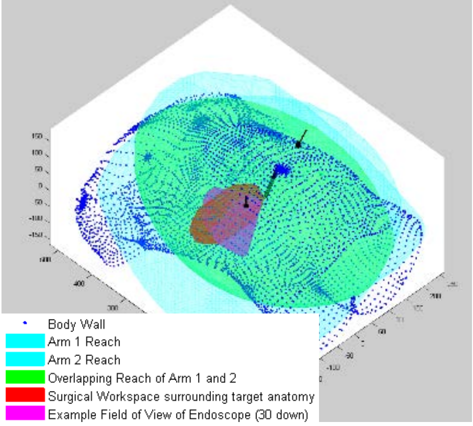


Figure 2: Overlapping cones of reach for a defined port placement and their access to an ellipsoidal workspace

Spar Interference

Spar interference was another criterion of the optimization. When surgeons experience spar interferences, it interrupts their workflow by stopping the procedure to take time to understand what is limiting their motion. Spar interferences can become especially disruptive when spar features (i.e. the carriage) become interlocked, making it hard to move freely. Interferences, specifically of the spar, were focused on because they are heavily dependent upon port placement, whereas other types of interferences are more dependent upon setup joint (SUJ) positioning.

Spar interference is difficult to predict because it considers two dynamic objects of unknown interdependency and how they may attempt to occupy the same space. This is why the evaluation of spar interference had to be approached as a relative probabilistic model. By this, it is meant that the absolute likelihood of experiencing interferences is too difficult to calculate due to complexities and considerations that cannot be predicted. Therefore, the estimated probability of interferences for one set of ports with respect to the estimated probabilities for other sets of ports must be evaluated. The following paragraph outlines how relative probabilities of spar interferences were calculated.

By placing a port at a location on the body wall, lines may be drawn from the port to every point that lies within the surgical workspace that was previously defined while considering reach. Each of these lines has the same angle as the line made by the spar when extrapolated beyond the body wall. Around each of these lines exists a cylinder in which the spar may be located. Using geometric equations, it may be determined whether a point lies within the volumes of these cylinders. By mapping the union of all of these cylinders, the swept volumes likely to contain the spars for a given procedure may be mapped. When multiple spars' volumes are mapped, the volumes of their intersections with one another may be found (shown in figure 3).

With a zero or near zero intersectional volume, spar interferences are still possible, but they are very unlikely. With a 100% or near 100% intersectional volume, spar interferences may not occur, but they are very likely. The intersectional volume may not linearly relate to the rate of spar interferences, but it is assumed that a smaller intersectional volume will have a lower rate of spar interferences. The score that is returned for spar interference equals the percent of swept spar volume that is not in intersection with another.

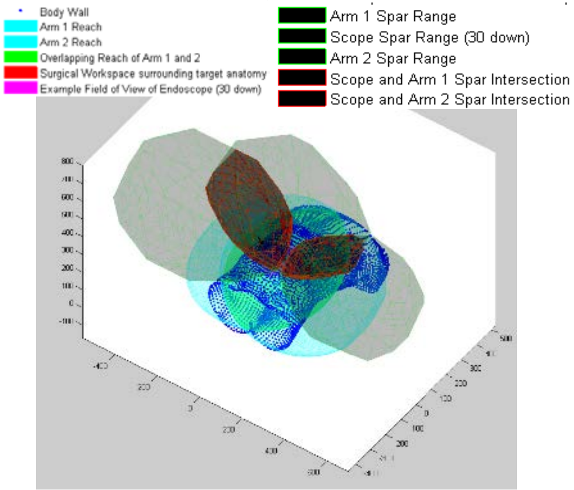
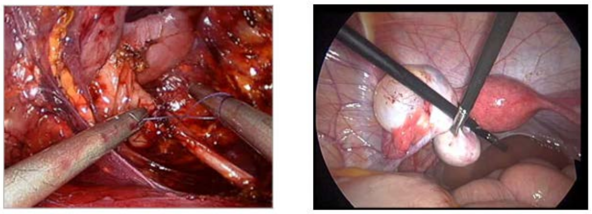


Figure 3: Map of likely spar locations, including interferences

Anthropomorphicness

Anthropomorphicness was implemented as a criterion to consider human factors and go beyond simply ensuring reach and minimizing interference. There are several locations on the body wall that perform well with respect to these criteria, but they can result in awkward orientations for the surgeon. Instruments shouldn't enter vertically from the middle of the top or bottom edges of the field of view (FOV). Likewise, it would be unnatural to have the arms entering from the horizontal bisector of the FOV or higher. When the instruments enter the FOV from the bottom corners of the screen, a more natural hand-eye familiarity can be provided to the surgeon (shown in figure 4).

The scope's FOV projected through space is found to be a pyramid, and the equations of the planes that define the diagonal bisectors of that pyramid can be found geometrically. The camera port was set at the umbilicus because that is the most commonly used location for cholecystectomies. By directing the scope (0 or 30 degrees up or down) at the center of the workspace, 50 mm away (a typical working distance), the nominal FOV can be found. By placing the instrument tips at the center of the workspace, the nominal instrument shaft angles may be found with respect to the planes that diagonally bisect the FOV. An instrument that has a 0 degree angle is considered optimal as it would lie within the diagonal plane, which indicates that the instrument enters from the corner of the screen. This angle can be normalized on a 0 to 90 degree range to give a score out of 100. This score can then be weighted together with spar interferences to output an overall score for each set of ports.



GOOD AWKWARD

Figure 4: Good and awkward instrument positions, that are optimized through the anthropomorphic criterion

Implementation

After verifying the geometry, the methods were integrated into an optimization algorithm. The optimization samples port placement sets at regular x-y intervals, projected onto the body surface, across the body wall, calculates scores for each set, and then returns the location of the set with the maximum score. This was first performed on a theoretical model of a 50-percentile male for the example procedure, cholecystectomy. After evaluating the results of the theoretical model, the algorithm was modified to work in a lab setting on an actual model.

To make the algorithm work in a lab setting, a method was needed to input the patient's body habitus data. *Structure* (Occipital, Inc., Boulder, CO), an iPad-mounted 3D scanner, was used to generate a point cloud of the patient's abdomen following insufflation. Following scanning, the data was aligned to the proper coordinate system, and it was cropped to eliminate interfering data, using software called *Meshmixer* (Autodesk, San Rafael, CA).

RESULTS

Lab Setup

A cadaver lab was run to evaluate the port placement tool. The cadaver was an 89-year-old female with a BMI of 37.5. Following Veress needle insufflation, the cadaver was scanned with *Structure*. The scanned body wall data was sent from the iPad to a laptop and was cropped using *Meshmixer*. Following editing, the body wall data was input into the algorithm. Features were identified on the model that were used to align it to the coordinate system and define variables that are used in the algorithm to indicate target regions and keep-out zones for port placement. These features included the xiphoid process, the costal margin, the anterior superior iliac spine, the pubic symphysis, the umbilicus, and the estimated location of the gallbladder. Once these features were identified, the program began, and after about 10 minutes, the results were output.

The algorithm completed, outputting a left-hand instrument port to be placed 127mm lateral patient right and 69mm inferior to the umbilicus, and a right-hand instrument port to be placed 40mm lateral patient left and 141mm superior to the umbilicus (shown in figure 5). A laparoscopic assist port was also placed for retraction purposes anterior to the target. All measurements were taken in a plane parallel to the floor before going into reverse Trendelenburg, to match the Cartesian coordinate system outputs from the program. The program found that the optimal score was 94.8 with an interference score of 93.7 and an anthropomorphic score of 95.8. The ports were evaluated during the lab with several pass/fail test cases. The results of those test cases are listed in the following sections.

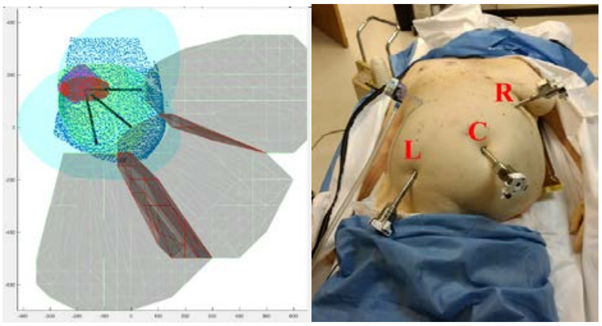


Figure 5: Cadaver lab program output (left) and physical port placement (right)

Lab Evaluation

Placing Ports

The algorithm did not output impossible port locations (i.e. too inferior, too lateral). The algorithm did not output ports that interfered with bony features. The port placement did not have to be adjusted for any other reason (i.e. blood vessels, ligaments).

First Tool In

All ports could be visualized by the endoscope when docked to the robot. The instruments were easy to follow during insertion. Zero spar interferences were experienced during first tool in with the robot.

Following/Procedure

The target anatomy could be sufficiently reached by the robot. The tools felt natural/anthropomorphic when manipulating the target anatomy. Zero spar-to-spar interferences were experienced during the procedure. Zero spar to patient interferences were experienced during the procedure. Some interferences occurred with the laparoscopic assistant and assistant port, but this was not troublesome.

General Evaluation

The results strongly supported the hypothesized optimal port locations. The instruments had sufficient reach as they could reach as superiorly as the diaphragm and as far laterally as both lateral body wall surfaces. Spar interferences were optimal as zero spar-to-spar interferences were experienced during the entire procedure, including first-tool-in. The anthropomophicness of the ports was found to be good, but not great, which was probably a result of user error. The tools were often coming into the FOV too laterally, but this was likely due to misidentifying the surgical workspace as being located too far anteriorly. Most of the precise dissection work of a cholecystectomy is performed on the Triangle of Calot, which lies more posterior to the center of the body of the gallbladder during retraction. If this user step was corrected to place the center of the workspace more posteriorly within the body, more optimal results in terms of anthropomorphicness would be expected.

INTERPRETATION

Sources of Error

Although this algorithm produced positive results, several assumptions were made that likely introduced some error. The reasoning behind these assumptions, the error these assumptions introduced, and potential mitigations are to be addressed in this section.

The vectors defining the center of ROMs of the instruments was assumed to be equal to that produced by a nominal setup. This model was meant to decouple port placement from SUJ pose and PSC approach, but some calculations required a nominal value. This assumed centerline value could be removed if a SUJ pose optimization were run in parallel with port optimization.

Some other assumptions were built into the spar interference calculation. For example, sometimes tools leave the workspace to pick up a dropped clip or needle, and this type of scenario is not accounted for. It is not possible to account for every possible scenario, but this model is meant to represent those that are most common. This model also does not include internal degrees of freedom of the instrument tips (wrist angle), so the linear extrapolation assumption may be introducing some error. However, the effects of the internal degrees of freedom are very minor when determining spar angle so this assumption remains valid, especially when considering how this is a probabilistic model and not an absolute one.

Since there was a lack of data on what determines optimal anthropomorphicness, the assumption was made that tools feel most natural when coming from the corners of the screen. Although this assumption does not have supporting data, no reason was found to consider it unreasonable or invalid. It may be found that a slightly wider angle or slightly narrower angle of instrument shafts are actually optimal. It may even be found that the acceptable angle range may be larger than expected or it may vary based on the individual user. A human factors study may be performed to assess this claim, but until then, this assumption will be used, which may potentially introduce some error.

Although the goal of this tool was to be analytical in its approach, the criteria were defined and weighted somewhat subjectively. The weighting of spar interferences and anthropomophicness were set as being equal, but they may not be. It may be possible that other important criteria were missed, such as issues concerning line of sight or spar-to-patient interferences. As this tool is further tested, if these issues exist, they are expected to reveal themselves, at which point they can be addressed and tuned.

Lastly, there is potential for user error and error due to anatomical variation. An input for location and size of the surgical workspace is user defined, which is determined based on external anatomical features. Anatomical variation may cause the target tissue to be in a different location than is indicated by the external features. Even if the target is in the typical anatomical location, there is still potential for the user to misidentify that location, introducing a source of error.

Conclusions

Despite several potential sources of error, early results show that this tool is capable of producing good recommendations for port placement. Although cholecystectomy is a relatively simple procedure, the principles that were developed in this tool could help guide surgeons with procedures in which port placement is a much more critical step. Furthermore, this algorithm has the power to give custom recommendations that are highly patient specific. By providing surgeons with this customized port placement optimization for each patient across every procedure, consistently superior port placements could be expected, leading to better, more efficient surgery.

REFERENCES

1. Köckerling F. Robotic vs. Standard Laparoscopic Technique – What is Better? Frontiers in Surgery. 2014;1:15. doi:10.3389/fsurg.2014.00015.
2. Yeo, S.A., Noh, G.T., Han, J.H., Jeong, H.H., Cheong, C., Stein, H., Kerdok, A., Min, B.S. (2017). Universal suprapubic approach for complete mesocolic excision and central vascular ligation using the da Vinci Xi® system: from cadaveric models to clinical cases. J Robotic Surg doi:10.1007/s11701-016-0664-y