Performance Assessment and Optimization of Motion Planning in a Surgical Trainer for Potential Space Applications

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Abstract— **Medical surgeries in the space environment, including long term space travel (e.g., to Mars) and permanent presence on other planetary bodies (e.g., Moon and Mars), are posing an inherent logistical, and in the absence of appropriately trained personnel (i.e., surgeons), even a potentially life-threatening challenge. As a potential mitigation the use of an existing surgical trainer tool that would allow crewmembers to acquire basic surgical skills is proposed, and to train space station personnel both in space and on the Moon and Mars to hone these skills long-term. Furthermore, this tool would potentially allow for tele-conducted surgeries, akin to the da Vinci Surgical System, controlled from Earth but executed onboard, e.g., the International Space Station. On Earth the surgical trainer can be used to train surgeons and flight surgeons. The efficiency of any surgical training system plays a significant role in its reduction of operative risks and stress associated with insufficient experience of the trainee. The primary goal of such systems is to raise the trainee to a higher level of proficiency without putting patients at risk in the operating room. The prototype for the Computer Assisted Surgical Trainer (CAST) being developed at the University of Arizona realizes an optimal motion-planning algorithm. The underlying system consists of mechanical fixtures equipped with encoders and DC motors. This hardware provides a means to accurately track the tip movements of laparoscopic instruments used in minimally invasive surgery. Furthermore it provides haptic and visual feedback to trainees by using a PID controller and augmented reality visualization. Examples of surgical guidance and the improvement of surgeon performance over time using CAST are presented.**

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1. INTRODUCTION

Long duration spaceflight, such as for and during a permanent human presence on the Moon and future human missions to Mars, will require autonomous medical care to address both expected and unexpected risks. Medical surgeries in the space environment are posing an inherent logistical, and in the absence of appropriately trained personnel (i.e., surgeons), even a potentially life-threatening challenge. As a potential mitigation the use of an existing surgical trainer tool that would allow crewmembers to acquire basic surgical skills is proposed, and to train space station personnel both in space and on the Moon and Mars to hone these skills long-term.

The development of *intelligent surgical training systems* is a novel research direction that is expected to play an increasingly important role in teaching basic laparoscopy skills to space station personnel both in space and on the Moon and Mars. The aim of such systems is to provide continuous guidance on optimal, safe navigation along with augmented visual and haptic sensory information. Furthermore, this would potentially allow for tele-conducted surgeries akin to the da Vinci Surgical System controlled from Earth but executed onboard, e.g., the International Space Station (ISS).

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The *Computer Assisted Surgical Trainer (CAST)* [1, 2, 4, 5, 6] is an intelligent surgical training system that benefits from high flexibility, visual guidance and haptic feedback and independence from expert surgeons' active assistance. The prototype for CAST is being developed at the University of Arizona with the primary goal to raise the trainee to a higher level of proficiency in surgical skills in general, and for use by crewmembers and space station personnel both in space and on Moon and Mars in particular.

The underlying system consists of mechanical fixtures equipped with encoders and DC motors [1]. The system has a basis in research that has shown that the combination of graphical and haptic guidance is an effective technique in achieving optimal path enumeration in a three-dimensional space. The implementation of a graphical guidance system focuses on designing multiple three-dimensional perspectives and visual cues to aide users in navigation. These designs focus heavily on augmenting human visual perception in a visually limited environment with multiple obstacles along with augmented reality visualization [3]. The haptic feedback to the trainee, is done by using a PID controller, complements the graphical guidance system by providing a tactile dimension. The implementation focuses on the design of a multi-axis control system and a real-time reference path generator. These implementations provide a full-spectrum navigation system that train users in optimal path enumeration given a limited perceptual environment.

The *optimal path generation (OptMIS)* [2] is an important part of CAST. The algorithm generates the optimal path for the fixed training workspace. According to this approach, the Delaunay tetrahedralization algorithm [7] is used to split obstacles into tetrahedrons and to derive the free space so that all tetrahedrons located in this free space comprise the search space of the optimal motion planning method. Dijkstra's algorithm [8] defines tetrahedrons that correspond to promising areas in the space. An enumerative combinatorics technique exhaustively explores the selected areas of interest to provide more accurate solutions to the problem. Cubic spline methodology [9] helps in constructing realistic smooth paths to prevent zigzag movements of the laparoscopic instruments. The points selected for drawing the optimal path are checked with the points contained in the objects in order to reject points that lie within the objects for collision prevention. A typical optimal path for this fixed workspace is generated in about 700 seconds, computed by profiling the software program in the MATLABR2009a profiler on an i5 Dual-core Macbook Pro at 2.3 GHz.

In the proposed work, the Path generation process is optimized by generating optimal paths for a given training scenario in a more time efficient manner. This will afford the system more flexibility and robustness to switch between multiple training scenarios by speeding up the path generation process. Secondly, this may be the initial step that will allow us to dynamically generate optimal paths in changing environments.

2. RELEVANCE TO NASA AND HUMAN SPACE FLIGHT

The operational space environments, such as aboard the International Space Station, or during future long duration space missions to or permanent presence on the Moon and Mars, present numerous risks to crew health and performance. The international space community and space agencies in general and NASA in particular are actively studying these risks and mitigation techniques. Crew health and performance are essential to successful human space exploration.

Popov et al. (2013) point out that rather than having to treat the occurrence of adverse health conditions in astronauts, the emphasis should be on their prevention and prediction [10]. This notion is also shared in the 2013 "Global Exploration Roadmap" report, published by the International Space Exploration Coordination Group (ISECG) in August 2013 [11]. The report lists the following key supporting objectives to develop space exploration technologies and capabilities [11]: test concepts, approaches, countermeasures, and techniques to maintain crew health and performance.

Human space missions going beyond Low Earth Orbit will require technology solutions for crew healthcare to address physiological, psychological, performance, and other needs autonomously in-situ, i.e., without immediate Earth-support or Earth-control. This is necessary because emergency or quick-return options will not be feasible. Therefore, onboard capabilities that would allow for early self-diagnosis (e.g., [10, 12]) of impending health issues, and autonomous identification of proper countermeasures early on are essential.

Despite best efforts mentioned above, adverse conditions can develop, e.g., due to an accident causing injury to a crewmember or astronaut, which may make surgical procedures necessary. In the absence of qualified medical personnel (i.e., surgeons), such situations will pose a logistical if not life-threatening situation. It is in these cases, where robotic surgical systems (e.g., [13]) or intelligent surgical training and guiding systems, as introduced in the following, can make a (life-saving) difference.

3. RELEVANCE TO MINIMAL INVASIVE LAPAROSCOPIC SURGERY

Da Vinci Surgical System [13] is a robotic surgical system designed to facilitate complex surgery using a minimally invasive approach, and is controlled by a surgeon from a console. The da Vinci System has a surgeon's console that is typically in the same room as the patient, and a patient-side cart with four interactive robotic arms controllable from the console. Three of the arms are for tools that hold objects, and also act as scalpels, scissors, bovies, or unipolar or bipolar electro cautery instruments. The fourth arm carries an endoscopic camera with two lenses that gives the surgeon full stereoscopic vision from the console. The surgeon sits at the console and looks through two eyeholes at a 3D image of the procedure, while maneuvering the arms with two-foot pedals and two hand controllers. The da Vinci System scales, filters and translates the surgeon's hand movements into more precise micro-movements of the instruments, which operate through small incisions in the body (i.e., laparoscopic surgery). By providing surgeons with superior visualization, enhanced dexterity, greater precision and ergonomic comfort, the da Vinci Surgical System makes it possible for more surgeons to perform minimally invasive procedures involving complex dissection or reconstruction. For the patient, a da Vinci procedure can offer all the potential benefits of a minimally invasive procedure, including less pain, less blood loss, and less need for blood transfusions.. The da Vinci system uses proprietary software, which cannot be modified by physicians, thereby limiting the freedom to modify the operating system. Furthermore, its $2 million cost places it beyond the reach of many institutions. [14].

The Computer Assisted Surgical Trainer (CAST) is an affordable, flexible, and portable device that is ideally positioned to offer training capabilities for a broad range of learners (e.g., medical students, residents, fellows, and practicing surgeons). Its potential in the context of human space flight is twofold: a) as a training system on which endoscopic procedures are exercised prior to a surgical intervention in space, and b) as a "tele-porting" system that is used to guide space station personnel how to carry out a complex endoscopic/laparoscopic procedure, should an emergency arise.

Offline Training scenarios can be set up to maintain skill levels and to exercise "dry-runs" in elective procedures. The "on-line", tele-porting assistive scenarios would involve highly skilled surgeons who use CAST as a "master" platform to guide space-based personnel through surgical steps. Here, CAST's parameters (e.g., instrument placement, position, movement, etc.) are transmitted in real time to space-based surgeons in Low Earth Orbit (i.e., aboard the ISS), who would then replicate the steps in vivo.

The CAST platform can be designed to perform automated or manual procedures. A use case diagram is shown in Figure 1 that captures essential functionalities. The key element is the base station where the expert surgeon would be present, who can upload training or surgery related information to the system on-board, and the astronaut can perform the procedure. The various tasks involve: choice of procedure, loading procedure manuals, performing the task, providing feedback, and dynamically improving the performance based on the task.

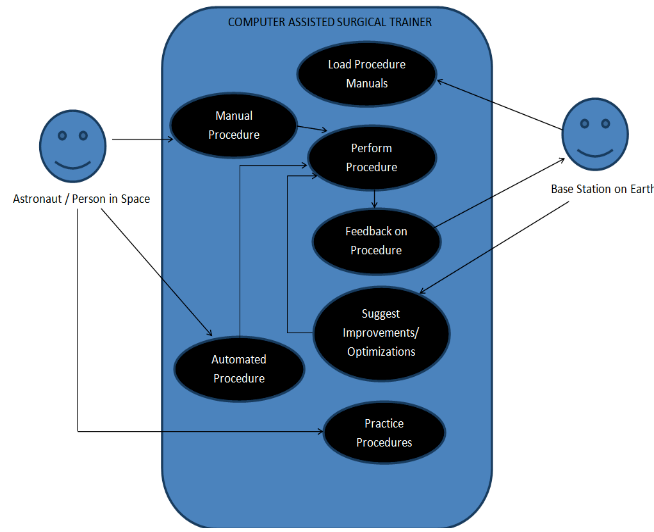

Figure 1: CAST Use Case Diagram

4. DESCRIPTION OF HARDWARE/SOFTWARE SETUP

The CAST design concept was driven by the need to simulate surgical procedures in stages, represent anatomical variations and anomalies, permit random introduction of unforeseen crises, and to provide haptic feedback with visual guidance by incorporating Augmented Reality. The system has methods and tools that track and assess trainees' performance. The CAST system architecture consists of five parts, as illustrated in Figure 2 that represent its elemental functionality.

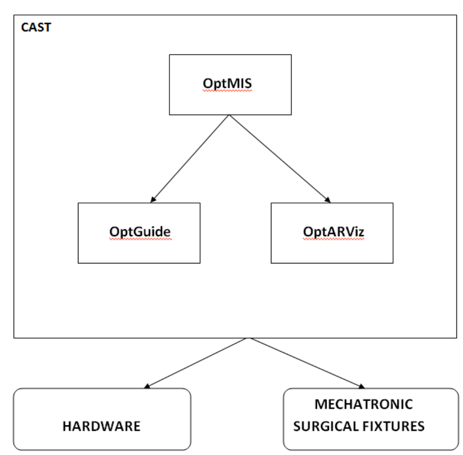

Figure 2: CAST System Overview

Hardware

The hardware for CAST consists of fixtures and electronics for haptic guidance and instrument tip position tracking. Figure 3 illustrates the hardware component of CAST. The mechanical fixture used in the CAST is an aluminum fixture with a gimbal that mounts a laparoscopic instrument measuring the yaw, pitch, insertion, and roll. Each shaft has a mount for motors. These provide haptic guidance to the user. A USB4 [15] module by US Digital is used to process encoder wheel positions and actuate motors. It connects back to a PC, which runs the CAST software. US Digital provides a software package that allows a PC to interface with the USB4 via a USB interface. Three ADS50/5 amplifiers are connected to the three motors in CAST III. The ADS50/5 connects with the CAST III electronics by two Set Value pins. One input connects from an amplifier that is amplifying a USB4 DA converter pin. The second input connects to a voltage divider providing 5V. In addition, there is an enable line used to turn a motor connected to an ADS50/5 on or off. Two inputs (+Set Value and -Set Value) on the ADS50 connect to a differential amplifier. The magnitude of the voltage difference is linearly correlated with the motor speed. The sign determines the direction of rotation. A non-inverting amplifier connects between the ADS50/5 and USB4 to compensate for the load difference between the two. The CAST uses two separate power supplies with two different voltages for the servo-amplifier motor system. One power supply provides 12V to the non-inverting amplifier. A second power supply supplies 48V and 576 Watts that powers all three servo-amplifiers and motors.

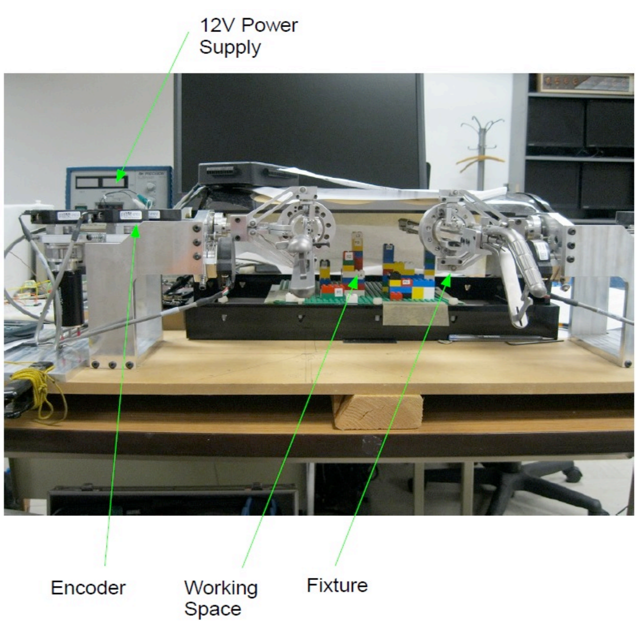

Figure 3: Hardware components of CAST

Software

The software system of CAST has three components which are: OptMIS, OptGuide and OptARViz. OptMIS, which is written in MATLAB, generates the necessary configuration files of the optimal paths for the fixed minimal invasive surgery model. This part of the CAST software works together with the guidance system (OptGuide) and the Augmented Reality visualization system (OptARViz) [3]. OptGuide is the haptics control system. Its main role is to provide the control algorithm for haptic feedback. The control architecture is derived from preliminary work to define a control algorithm to enumerate optimal paths generated by OptMIS. The OptARViz, written in C++ using the Visualization Toolkit (VTK), uses the outputs of OptMIS in order to display the optimal path augmented on the real world display along with the necessary target points. This guides the trainee in order to perform the specific surgical task.

OptMIS generates the optimal path configuration files in around 700 seconds on an i5 Dual-core Macbook Pro at 2.3 GHz, thus hampering the full potential integration with OptGuide, OptARViz, and the Hardware, which a real time implementation would otherwise provide. Section 5 discusses in detail OptARViz and OptGuide, and Section 6 will further discuss OptMIS and its performance. It also discusses the optimization of OptMIS using MEX files [16] that call for a low level compiled language like C/C++ from within the Matlab code to generate the configuration files in a time efficient manner on a route to reach real-time performance.

5. PID Controllers And Augmented Reality

The purpose of designing the OptGuide and OptARViz modules is to provide better hand eye coordination and depth perception to the novice trainee. Haptic feedback and augmented reality are used to enhance the training environment. Whenever the instrument tip deviates from the optimal trajectory, OptGuide applies force to navigate proper moving direction, and OptARViz shows current tip location with additional information for trainee to move the instrument to the correct position.

Both haptic feedback and visual guidance use the optimal path generated by OptMIS as a reference input and the actual tip position captured by the encoder unit. The reference generator has been designed to find the nearest reference point based on actual tip position and optimal path. Both, reference point and actual tip position, are updated at every sampling period, i.e., 50ms.

OptGuide

OptGuide has an individual position based proportional-integral-derivative (PID) controller for each degree of freedom [17]. The PID controller is implemented in discrete time domain based on the following equation:

$$u(k) = u(k-1) + k_p\{e(k) - e(k-1)\} + k_i T_s e(k) + \frac{k_d}{T_s}\{e(k) - 2e(k-1) + e(k-2)\}$$

where u(k) represents the output of the PID controller and e(k) represents the error between the reference input and the actual tip position. There are three controllers for yaw, pitch, and insertion axes. Each axis has different physical characteristics. Therefore, a different set of gain parameters for each degree of freedom was used to make the system stable and to include different characteristics of each axis. Figure 4 shows the overall block diagram of OptGuide.

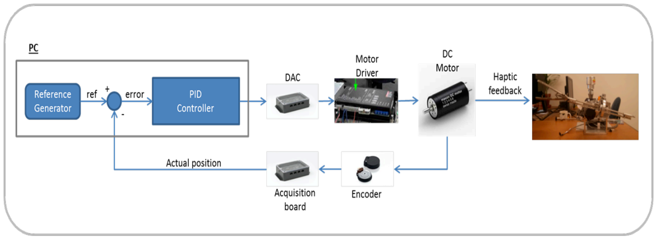

Figure 4: OptGuide Functional Block Diagram

To tune each gain parameters, a DC motor model was created and simulated to find proper gains, which are satisfied, stable conditions. After that, fine-tuning was performed based on experimental results using the CAST hardware.

OptARViz

This module is used to enhance depth perception, hand eye coordination, which are major challenges faced by surgeons and trainees [18]. When a trainee observes a real world environment on a 2D monitor, it becomes a challenge to perceive depth accurately. OptARViz describes the visualization system, using augmented reality, which attempts to solve this problem. This module can be described in two parts:

1. Camera Calibration
2. Overlay using Augmented Reality.

Camera Calibration is a technique, which maps points on the real world to where they correspond on the image. The assumption made here is that the camera will be kept at a fixed location during training. It relies on generating a Camera Matrix, which is the transform between real world coordinates and homogeneous coordinates. In order to generate the camera matrix, a calibration rig with known coordinate locations is provided. The CAST block world-training scenario is used as the calibration rig. The camera matrix computation is performed by considering the eigen vectors corresponding to minimum eigen values [19]. In the next step, the optimal path generated by OptMIS is applied as an input to the camera matrix. This provides us with the optimal path in image world coordinates.

Overlay using Augmented Reality is achieved by modifying the following actors in the visual scene: Optimal Path, Instrument Tip and Crosshairs for Depth Perception. These visual cues tend to provide assistance to the trainee as he navigates on the optimal path to complete the training task and are depicted in Figure 5.

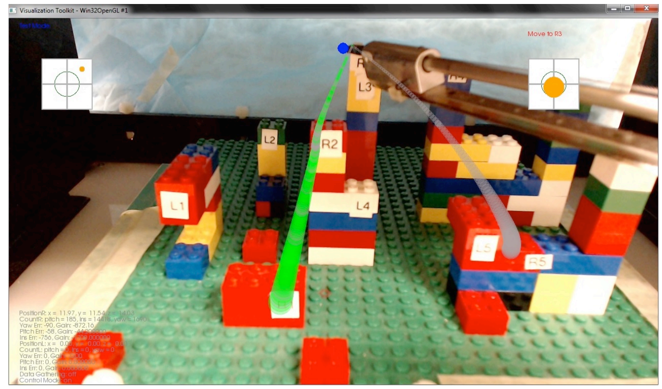

Figure 5: OptARViz Visualization

6. OPTIMAL MOTION PLANNING

A key component of the Computer Assisted Surgical Trainer system is the optimal motion planning method (OptMIS) developed to find shortest, collision-free trajectories for laparoscopic instrument movements. The present CAST is based on a fixed training model involving the use of blocks as the obstacle space and navigating the laparoscopic instruments through this obstacle model. Since laparoscopic instruments are fixed at the pivot points, their movements are limited to 3 degrees of freedom (DOF) with a reduced range of motion. Thus, each configuration $s_i(t)$ of the i-th instrument at time t can be represented using three parameters: pitch $\alpha_i(t)$, yaw $\beta_i(t)$ and insertion depth $\gamma_i(t)$. The pitch and yaw describe a limited inclination of the shaft pivoted through the incision, while the insertion depth determines translation along the shaft of the instrument. Rotation is not considered, because it does not change the position of the instrument in the workspace. Given these definitions the motion planning method is mathematically formulated for each i-th laparoscopic instrument given a sequential set of configurations $S_i \in C_{free}$ where C_{free} represents the configuration of the model without obstacles, which is called the free space:

1. All target configurations $\subseteq S_i$ are involved
2. The total length of the curve connecting all targets is the minimum of all possible path lengths.
3. No S_i intersects any obstacle
4. S_i satisfies the non-penetration constraint (i.e., two laparoscopic instruments must not share the same space.

The following steps are designed to solve the above-formulated problem:

1. *Work space representation (Obstacle space and Free space):* The obstacle space in our training model consists of solid static obstacles. The use of polyhedron representation [20] benefits from high accuracy and simplicity. The Delaunay Triangulation algorithm [7] is used to split the working space into tetrahedrons. The

tetrahedrons that intersect with the obstacles or the surgical instrument are rejected with the provision that the instrument has been represented geometrically as a cylinder of known radius. In contrast to the method of alpha shapes [21, 22], our method provides more flexibility in modeling complex obstacle spaces and is independent of other parameters.

2. *Pre-processing of Search space:* The space presently divided into tetrahedrons is the search space for the optimal motion planning. The tetrahedrons have information of their neighbor tetrahedrons and the coordinate information of their centroids. Using neighbor information an adjacency matrix is formed that gives information about the neighbors of a particular tetrahedron. Using the adjacency matrix the centroids of the respective tetrahedrons are extracted, forming the search space to find the optimal path.

3. *Defining the search strategy:* The offline search strategy [23] provides a global perspective for solving the problem. Although the offline search strategy is not as flexible as the online search strategy [23], which allows movements of the instrument in an uncertain environment. In CAST, with the obstacles being known, offline search strategy better suits this application. Our emphasis is on training and it is better to capture the problem features from a global perspective.

4. *Shortest path planning:* With the start and the goal positions known and the search space defined, Dijkstras Algorithm [8] is used to find the shortest feasible path without the need for solving time consuming k-shortest path problems [24].

5. *Construction of shortest curve:* An enumerative combinatorics technique exhaustively explores the selected areas of interest to provide more accurate solutions to the problem by finding data points that give the minimal length of the curve. Cubic spline methodology [9] helps in constructing realistic, continuous, and smooth paths.

The OptMIS program is written in MATLAB because of MATLAB's ease of use with built-in toolboxes for the various steps mentioned above and the convenient matrices and function plots. However, the performance of MATLAB is inefficient in terms of speed. This hampers OptMIS, which is designed to switch between multiple training scenarios and realize dynamic, and potentially real-time path planning for changing environments. To mitigate this, the performance of OptMIS is assessed and MEX files are incorporated for time improvement, keeping most of the MATLAB code structure of OptMIS intact.

The OptMIS code is profiled in order to detect only those sections of the code that hamper the performance. The MATLAB Profiler [25] is a tool that provides an in detail measure of time that a program takes to run including time taken by the functions and their sub- functions. The code of OptMIS discussed in [2] is profiled using MATLAB R2009b profiler and run on a dual-core i5 Macbook Pro at 2.3Ghz. The sections of the code that are the most time consuming, taking into account the CPU time, are selected for optimization. MEX files allow MATLAB to call C functions, hence taking advantage of a compiler language to speed up an interpreted language like MATLAB.

The results of our performance assessment and the improvements of using MEX files in comparison to MATLAB alone for OptMIS are discussed in the Section 7.

7. RESULTS

The MATLAB R2009b profiler is used to profile the OptMIS program discussed in [2] in order to assess its performance. The profiling resulted in a time of 697 seconds. A bulk of this time is taken by the expansive collision detection of the optimal path and the surgical instrument with the object space. The rest of the time is consumed by certain functions as combinations and smoothing. Self-time is defined as the time spent by the function in itself plus some overhead in profiling. It is observed that the self-time is less in most of the time consuming functions of OptMIS. However, for functions, which check for object collision, the self-time is high as there is an elaborate check of the presence of the points of the optimal path/instrument cylinder in the object space. Figure 6 shows the results of the profiling of the original OptMIS code.

Function Name	Calls	**Total Time**	Self Time*	Total Time Plot (dark band = self time)
optMIS_console	1	697.066 s	0.212 s	
optMIS_console>findPaths	1	695.926 s	0.123 s	
optMIS_console>combinations	4	601.037 s	7.699 s	
optMIS_console>smooth	2	601.037 s	0.000 s	
optMIS_console>instrOutsideObstacles	184624	566.163 s	322.391 s	
optMIS_console>genCylPoints	184624	243.771 s	29.767 s	
optMIS_console>genCyl	184624	214.004 s	213.982 s	

Figure 6: Timing profile of OptMIS

The following functions are chosen as they have sub-functions in them that will be run much faster in a compiler language like C. The "smooth" function calls the "combinations" function and the "genCyl" function in turn. Thus, reducing the time in the child functions would reduce the time in parent function and this would reduce the overall time of OptMIS. The rest of the functions are ignored as they include functions that would work more efficiently in MATLAB.

The approach to improve the performance of these functions is by the use of MEX-files. Since MEX-files allow MATLAB to call C function within them, this compiler language can be used to improve the performance of the code and, for future work, it can be used to run on a hardware/FPGA device. Hardware/FPGA was not the most optimal approach for the speedup in the case of OptMIS as the data size involved in the calculation of the optimal path in OptMIS was over 8,000 node structures, which would result in memory issues on the hardware/FPGA device. Also, there is a need to run portions of the OptMIS using a compiler language as this will provide us the actual compile time on the machine.

Hence, by using MEX files the optimal path is generated in a much more time efficient manner, which will promote real-time performance.

The details and improvements of the above-mentioned functions are discussed below:

1. *"Combinations":* This function generates all possible combinations of points around the optimal path points and checks if these points intersect with the obstacle space. Also, it checks if the simulated surgical instrument as a cylinder around these points intersects with the obstacle space. The points that intersect with the obstacles are rejected. The portion of the code that generates all the possible points is selected for conversion to MEX. The time difference between the two is shown in Figure 7. It is also observed that the MEX file takes negligible time to run.

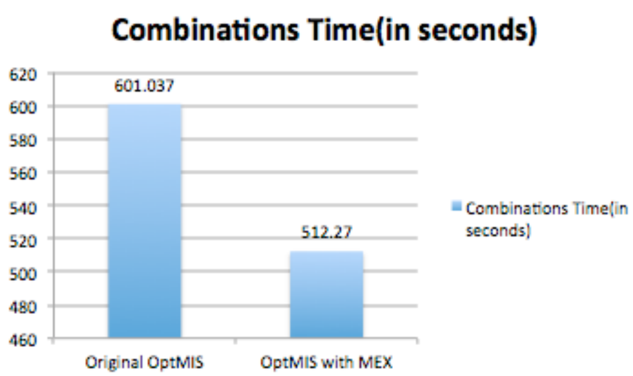

Figure 7: Graph comparing timings of combinations function in the original OptMIS and OptMIS with MEX

2. *"Smooth":* This function smoothens the optimal path generated by Dijkstra's algorithm. The points generated by the "combinations" function are used to draw the smoothened curve using cubic spline interpolation. Portions of the built-in cubic spline interpolation MATLAB function are converted to MEX. However, this does not show significant improvement in the run time. The improvement shown in Figure 8 is due to the improvements in its child function "combinations".

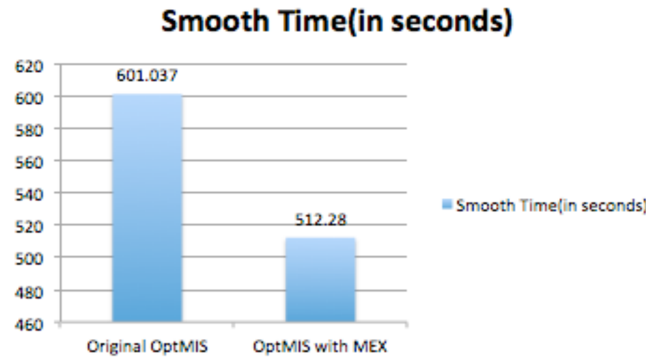

Figure 8: Graph comparing timings of smooth function in the original OptMIS and OptMIS with MEX

3. *"genCyl":* The "genCyl" function generates the cylinder that simulates the laparoscopic surgical instrument. It uses an built-in MATLAB function "cylinder" which generates a cylinder given its radius and number of equally spaced points around its circumference. Also, this function includes some computation intensive code for calculating the rotation of the cylinder around an axis. Hence, these sections along with the "cylinder" function are converted to C using MEX files. The MEX files for these sections take negligible time to run. Figure 9 shows the improvement in runtime.

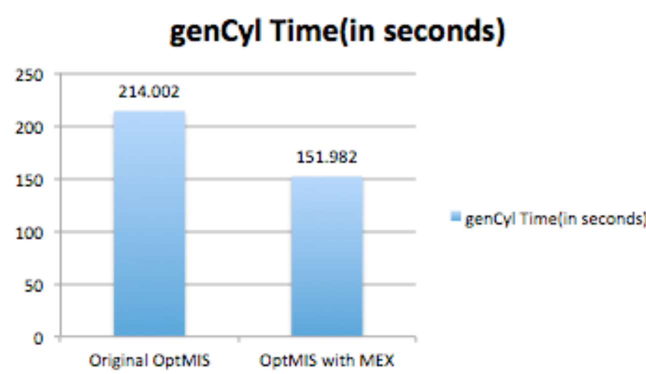

Figure 9: Graph comparing timings of genCyl function in the original OptMIS and OptMIS with MEX

The above improvements in the functions boost the overall time of OptMIS considerably. The speedup of OptMIS by using MEX files is by a factor of 1.265, which translates to a running time improvement of 146.401 seconds. Figure 10 shows the improvement of OptMIS by converting the essential parts of the code to more efficient MEX files.

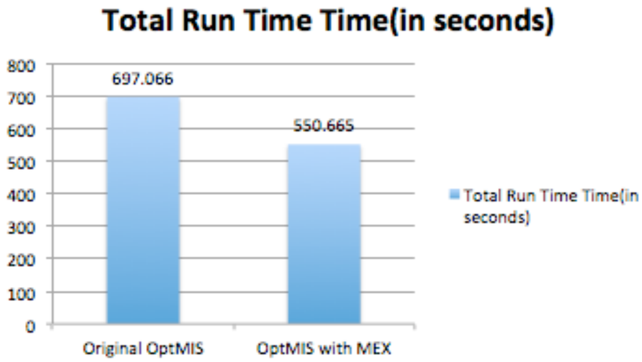

Figure 10: Graph comparing the overall time of the original OptMIS and optimized OptMIS with MEX

8. Conclusions and Outlook

This paper analyses the performance of the Optimal Motion Planning (OptMIS) in the Computer Assisted Surgical Trainer (CAST). We have analyzed portions of the MATLAB code that will be more advantageous in terms of performance by converting them to the C language. We implement an optimized OptMIS by using MEX files, keeping the main framework of MATLAB intact for its usefulness in various aspects of manipulating figures, mathematical operations, and matrix manipulation. As future work, we envision to implement these portions of the code and manipulate other parts of OptMIS to make it suitable for running on FPGA/hardware systems in order to achieve real-time performance.

Depending on the urgency of diagnosing a condition affecting the performance of an astronaut/crewmember, and depending on the communication bandwidth and delay, the intelligent surgical training and guiding system introduced here could provide for two distinct modes of operation:

1. *True telemedicine:* an Earth-based surgeon tele-conducts a surgical procedure onboard the ISS akin to the Da Vinci Surgical System [10];

2. *Autonomous in-situ:* a crewmember or astronaut conducts autonomously in-situ, i.e., without Earth-control, a surgical procedure on a fellow crewmember or astronaut. This modus operandi is especially called for during long duration space flight, or in a human outpost/settlement on the Moon and Mars, in the absence of Earth-bound expert input.

In summary, long duration spaceflight (e.g., trips to Mars) or a permanent human presence on the Moon and future space exploration missions to and eventual settlement on Mars will require autonomous medical care to deal with expected and unexpected risks. As such the use of expert systems [12], intelligent surgical training and guiding systems, and telemedicine procedures [12] is warranted, especially in light of the communication limitations and the lack of an in-situ clinical support infrastructure [10].

Acknowledgement

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