Development of a Robotic Surgery Game For Use As A Full Spectrum Engineering Project

THOMAS W. SECORD
Assistant Professor, University of St. Thomas, St. Paul, MN
and
ADAM GERENZ
Research Assistant, University of St. Thomas, St. Paul, MN

The authors have developed, fabricated, and tested a modified version of the Milton Bradley game of *Operation* for use as a full spectrum engineering project and teaching tool. The game trades the manual dexterity of the original gameplay for concepts from mathematics, physics, electrical engineering, mechanical engineering, and computer engineering. The object of the game is to use an industrial robot arm to execute ten surgical operations as quickly as possible. The robot performs surgical operations by hovering over the desired surgical position (e.g. funny bone) and transmitting an appropriate infrared signal with a custom-designed end effector. The game has been tested with junior and senior level high school students. The game itself has two pedagogical uses: design of the game components and gameplay. This work includes a description of the initial test and offers possible improvements and extensions to the game for both of its pedagogical uses.

1. INTRODUCTION

The use of games in the teaching of technical concepts has broad appeal from a pedagogical standpoint, particularly through increased student engagement and enjoyment. The increased engagement of the students is particularly likely if the game is an adaptation of one that may already be familiar and one whose rules can be scaled to many different levels of difficulty depending upon the student audience. Games that indirectly teach technical concepts (as compared to gamification of the content itself) are not particularly novel, but their effectiveness in teaching STEM concepts is widespread. For example, see [Ebner and Holzinger 2007], [Barata et al. 2013], and [Foster et al. 2012]. Furthermore, robotics has been used successfully as a focal point given its multidiciplinary nature [Beer et al. 1999], [Eguchi 2009]. Medical robotics is a particularly engaging area (e.g. see [Rockland et al. 2010]) and has therefore been selected as the theme for this work.

In this work, we adapt the Milton Bradley game of *Operation* for use as a full spectrum engineering project and teaching tool. Our pilot effort was tested with high school students and an industrial six-axis manipulator. The basic layout of the game is shown in Fig. 1 with additional detail provided in Fig. 2. There are two primary pedagogical uses for this game: gameplay and design of the game components, which we describe in the following sections.

2. GAMEPLAY

Gameplay provides opportunities for engagement at educational levels that straddle the undergraduate engineering curriculum: preschool through high school (i.e. years P-12) and graduate school (i.e. years 17-20). Gameplay excites and encourages the curiosity of younger children using robotic motion and an impressive audio-visual display. Many aspects of the game can also be made accessible for display to middle school and high school audiences. By contrast, gameplay offers advanced students a substantive introduction to applied combinatorics and robotics. Within combinatorics, the game teaches the solution to the canonical traveling salesman problem under imposed constraints wherein all operations sites must be visited as quickly as possible, yet the robot manipulator must not fly over an operation site before having operated there. Within robotics, the gameplay offers insights into manipulator kinematics, trajectory generation, control systems, robot programming, and coordinate transformations (e.g., what happens if the operating table and the patient are rotated?).

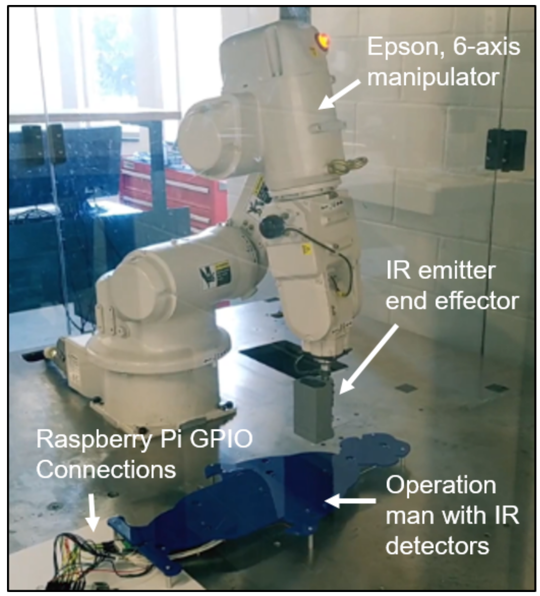

Fig. 1. Overview of the game and robot apparatus

The original gameplay design involves a form of the traveling salesman problem and was used with sophomore through senior-level high school students. Students were randomly grouped into teams of three. They were then giving the following problem statement:

> "A patient arrives to the emergency room and is diagnosed with several life threatening conditions including a bread basket, funny bone, and writers cramp! Time is of the essence for surgery! As the patient is prepped for surgery and moved to the operating room, you must plan the fastest path between all of the surgical sites. This hospital is equipped with ad-

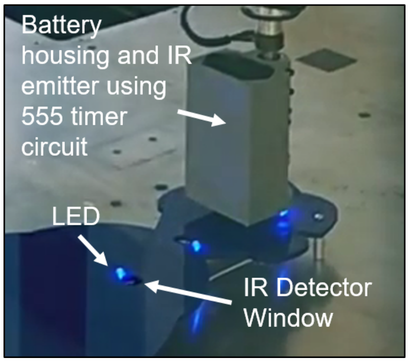

Fig. 2. Detail view during gameplay of the operation man and robot end effector apparatus

> vanced robotically positioned optical surgical tools. This makes the operations quick, but it means that you must not fly over an operating site unless you are operating there."

To help with the planning, students are given a dimensioned drawing and the matrix of distances as shown in Figs. 3 and 4, respectively. They are told to assume that the robot can be moved linearly at a constant velocity between any two points if there is a distance number listed at the adjoining row and column. For example, the first move from the origin can be to operate at any of the sites A through E because all of the associated entries have a listed distance. Therefore, moving from the origin to point A is allowed, yet it incurs a distance cost of 136 mm. For locations that are adjoined in the matrix with a blackened entry, such as the origin to operation site F (Bread Basket), this motion is not allowed because it would require the robot end effector (the infrared emitter) to pass over another operation site, in this case site H (Charley Horse). Given the foregoing information and constraints, the students were provided 20 minutes to plan what they thought to be the fastest route. The proposed routes were tested in a final competition. The time of each program is calculated accurately by the Raspberry Pi that runs the IR detection logic and LED display of the operation man.

Our observations during the initial offering of this game were that students relied on finding allowable surgical routes heuristically using the drawing (Fig. 3). A manual brute force search is impossible because, without reference to the fly-over constraints there are 10! = 3.63 million possible routes. Given the constraints, the number of possible routes reduces to only 36, yet this is unknown to the students and it still results in an onerous manual enumeration and search for the fastest route. Therefore, the reliance upon a graphical solution was expected. By simply using the visual planning, many student groups found a route that was close to the fastest theoretical route. This suggests that our version of the game lends itself well to an intuitive and visual solution.

Note that both Fig. 3 and Fig. 4 encode the same information. We believe this may provide a basis for interesting future research questions on visual versus analytical learning. Specifically, given only the matrix in Fig. 4 or only the dimensions in 3, what type of performance differences can we quantify in the solutions and time to arrive at solutions to this constrained traveling salesman problem? We hypothesize that an analytical approach may ultimately lead to faster overall solutions, but the time to arrive at the faster solution may actually take longer than a sub-optimal solution obtained graphically. We also believe that the results of the exercise

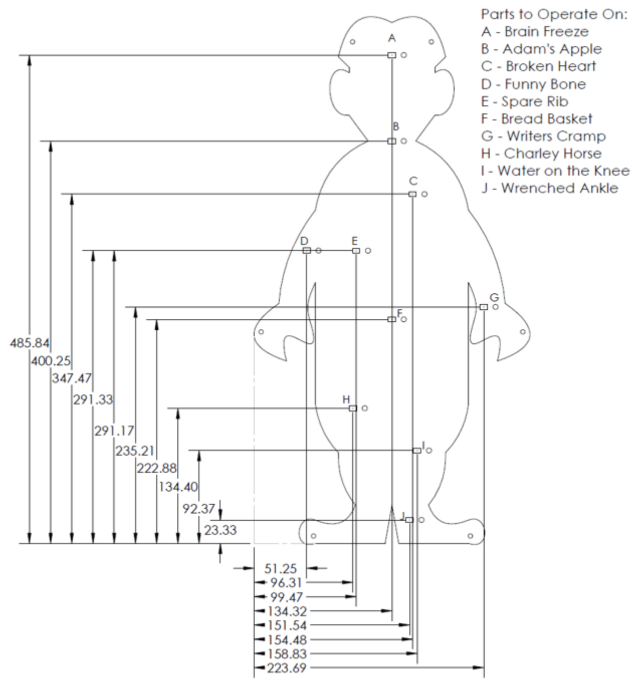

Fig. 3. Dimensioned operation man as used for the adapted robotic surgery game

	Origin	A	B	C	D	E	F	G	H	I	J
Origin		136	83	103	84	104					
A	136		86								
B	83	86		56	137						
C	103		56		118	86	126	132			
D	84		137	118		49					
E	104			86	49		68	132	147		
F				126		68		90	96	133	
G				132		132	90		162	157	
H						147	96	162		75	124
I							133	157	75		69
J									124	69	

Fig. 4. Matrix of allowable operation site transitions and their associated distances

may have been considerably different if the students were asked instead to find the slowest route.

Both the fastest and slowest routes can be readily obtained through a full brute force search or other combinatorial optimization algorithms. We wrote one such search program in MATLAB (which could also be assigned as part of this challenge). The results are shown in Fig. 5. The fastest route has the intuitive appeal of appearing as a loop that remains along an outer perimeter formed by the points. By contrast, the slowest route has no such intuitive interpretation. Note that in Fig. 5, the origin has been moved to the left of the operation man. The flyover constraints are still reflected accurately in Fig. 4.

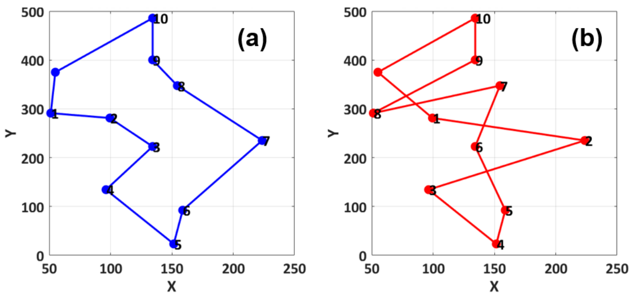

Fig. 5. (a) Fastest route obtained through a complete combinatorial brute force search. (b) Slowest route obtained through a complete combinatorial brute force search.

3. DESIGN OF THE GAME

The game design has three major components: a mechanical design, an electrical design, and a Python-based scoring program. This multifaceted structure makes this game particularly appealing as a tool that teaches basic design skills across many different engineering disciplines.

Design of the game components, offers teaching opportunities that are evenly distributed among theoretical calculations, computer aided design (CAD), programming, and hands-on fabrication. The design of the game components is well suited to both advanced high school students and undergraduate engineering students at various stages in their course of study. For example, teaching opportunities for electrical and computer engineering students include the selection of basic circuit components, design of a timing circuit, creation and capture of circuit schematics, oscilloscope-based measurements, band-pass filtering, printed circuit board layout, logic circuit synthesis, and an introduction to communication protocols. Similarly, crucial skills for mechanical engineering students include the creation of solid models, creation of engineering drawings, basic machining, static analysis of a robot linkage, laser cutting, 3D printing, and calculation of dynamic forces. Design of the game components also offers teaching opportunities for universal engineering skills such as project scheduling, work on multidisciplinary teams, and procedural programming in high-level languages such as Python and MATLAB.

4. EXTENSION OF THE GAME AND ITS DESIGN

The current game design and gameplay use the robot only for its basic positioning capability. Therefore, there are two possible extensions for the game that we are considering to adapt the game to different audiences outside the college level engineering curriculum. These are described in the following sub-sections.

4.1 Middle School to High School Level Gripper Design Challenge

We are currently exploring a modification of the game wherein the robot is used in conjunction with single degree of freedom student designed grippers. The actuation of the student grippers would be controlled in a pre-determined way through the robot program (e.g. when the robot gripper has reached the operating site, the gripper would be actuated after a 1 second delay). The students will be given simple materials and constraints on a gripper design. After a designated design period, student grippers will be tested in a final competition. Overall, this modification of the game will use the robot in a way that is more aligned with the original *Operation* gameplay.

Robot grasping is a notoriously difficult problem, however, and therefore care will need to be taken in the design challenge to ensure student designs will successfully achieve grasp stability of any gameplay object. We are avoiding the use of additional sensors and instead focusing on simple operations of picking up and placing the operation objects at a pre-programmed position. For example, a "Spare Rib" operation object may need to be enlarged and made more spheroidal from the original game in order to avoid a significant orientation dependence of the gripper. The intent of this design and game extension would be well suited to short (e.g. 1 day) STEM exploration sessions for students that may be considering STEM as a potential path of study.

4.2 Graduate Student Gripper Design and Kinematics Challenge

To adapt the game to the upper end of the educational spectrum, we are proposing an extension to the gripper design challenge wherein students are given a longer design period, fabrication facilities, and two or more degrees of freedom in the gripper. This will allow for more elaborate gripper designs that may be capable of playing the original game of operation without any modification. Alternatively, the game can be made even more interesting by imparting a more three-dimensional layout to the game board wherein the anatomical positions have a variable distance above the operating table. This version of the game may also require the use of machine vision to identify part orientations prior to robot motion and gripper actuation. The intent of this design and game extension would be well suited to a graduate level course in robotics.

5. CONCLUSIONS

The authors have developed an adapted version of the Milton Bradley game of *Operation* and used it successfully at an "Explore Engineering" high-school oriented session at the University of St. Thomas. Students were highly engaged in the gameplay and interested in the meta-engineering aspects of the game (i.e. the engineering that went into making the game intended to engage students in engineering). We therefore treat the game as having two main pedagoical uses: one wherein students simply play the game by set rules and one wherein students actually design the game components (e.g. as in a well-defined class project). Our initial results illustrate that visual solutions to complex combinatoric problems are often a useful heuristic. We hope to further quantify the difference between solution approaches in future randomized studies.

The main benefits of the game include a confluence of a familiar game (*Operation*), an industrial robot manipulator, a programmatic aspect (combinatorial optimization and robot manipulator programming), and scalability of the difficulty in the posed challenge. This makes our game distinct from challenges such as FIRST robotics wherein the challenge takes place over a longer period (6 weeks), involves a deliberately unfamiliar gameplay (i.e. a revealed challenge), focuses mainly at a high school audience, and utilizes mobile robots.

Numerous extensions and adaptations are possible for the proposed game and its design. We are therefore encouraged about the long term potential of this teaching tool for use in our technical curricula across the spectrum of possible student ages and abilities.

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