ENS4152 Project Development

Progress Report

**Baxter Research Robot: Solving a Rubik’s Cube**

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**Abstract**

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1. **Introduction**

**1.1 Introduction**

The Baxter Research Robot made by Rethink Robotics is a dual arm robot developed for research applications (Rethink Robotics, 2015). Each arm features seven degrees of freedom, allowing complex manoeuvers such as grabbing an object that is behind another. It was released in 2012 and designed to be affordable, flexible in its applications and above all else, safe. Baxter includes a total of three cameras, one on each wrist near the gripper, and the other on its head, which consists of a screen for displaying information such as Baxter’s current task. It is designed to work along humans without a safety cage and allows direct programming through an open source Robot Operating System (ROS) Application Programming Interface (API) (Rethink Robotics, 2014). This allows easy development of programs to run on Baxter, and aids research applications greatly. The Baxter Research Robot model uses the same hardware as its industrial counterpart which allows direct translation from research to industrial application.

Robotics in industry has been developing from simple single arm robots to multi robot work cells (Hajduk, Jenčík, Jezný, & Vargovčík, 2013). This has increased the complexity of tasks that can be completed by robots. Where multiple robots are used, each robot performs a sub task generally at the same time as the other robots, allowing not only an increase in productivity but the quality of products (Zhang & Ouyang, 2012). The tasks that can be completed have changed from being simple such as sorting into complex tasks that require multiple manipulations or actions to be performed at once, such as automobile welding. Further developments have seen the rise of dual arm robots. These allow robots to become more mobile while still providing some of the benefits of using multi robot work cells. Tasks traditionally performed by humans are now beginning to be completed by dual arm robots, whose range of motions resemble human abilities. More recently, artificial intelligence (AI) has begun to be combined with robotics to achieve a higher level of automation. AI currently is very focused, with well-developed areas of AI. Future developments in robotics will require a combining the areas of AI to allow robots a high level of automation, one day rivalling that of humans.

This project uses the Baxter Research Robot in developing an algorithm that combines the vision and servo systems of the Baxter with a solving solution. By developing this algorithm to enable Baxter to solve a Rubik’s cube, the use of dual arm robots for complex manipulation and the application of AI is combined. The project will use a vision system to analyse the cube, motion planning to manipulate the cube and a solving solution to determine the face rotations required to solve the cube.

A demonstration of the Baxter Research Robot solving a Rubik’s cube has been developed previously (Coles-Abell & Pugh, 2014). This was undertaken to demonstrate the ease of integrating Baxter Research Robot into a research application. They developed a workflow consisting of detect, verify, solve, manipulate and complete. Baxter was taught to use a flatbed scanner to image each face of the cube. To differentiate this project from theirs, no flatbed scanner will be used to image the cube, instead only the vision system available with Baxter will be utilized.

This project strives to show the application of simple AI with the Baxter Research Robot in completing a complex task. The task of solving a Rubik’s cube requires a visual analysis system to be combined with motion planning and complex manipulations of an object alongside a simple AI for solving the cube, thus demonstrating the added complexity of performable tasks to be completed when even simple AI is implemented.

Majority of the progress of the project has been research. A program called Cube Explorer 5.12 (Kociemba, 2014) has been found as an excellent solving solution and is available as an educational product. Through the use of a solving solution named the Two-Phase Algorithm developed by Kociemba, the cube is solved and a set of manoeuvres output. The solution can be found in nearly every case within a few seconds.

Research into an appropriate vision system has proved OpenCV to be optimal. It is an open source computer vision library that provides a library of algorithms, the most relevant being video and image analysis. No vision system has been developed yet as research into how OpenCV works and the algorithms it provides is still ongoing.

The required motions has not yet been developed but the tools outlined in the proposed approach will be used to plan these motions.

**1.2 Objectives**

The main object of this project is to develop an algorithm that controls and combines the servo and vision system of the Baxter Research Robot with a solving algorithm. This involves picking up the Rubik’s cube from a set position, visually analysing the Rubik’s cube, finding the solution to the cube, manipulating the cube and placing the cube solved back where it originated. This project is focusing on only using the Baxter Research Robot for both manipulating and visually analysing the cube, and as such the only hardware needed will be a computer connected to the Baxter Robot and the robot itself. The computer will be set up to communicate with the Baxter robot as a workstation.

The solving algorithm must present a list of moves that when performed on the Rubik’s cube, will result in solving it. This project is focusing on only the 3x3 Rubik’s cube. To solve the cube, either a set of rules for solving the cube must be followed, or a database of all solutions must be used. Using a data base of all solutions and looking it up is not only a long process, it’s also just getting a robot to do a predefined task. By using a set of rules for solving the cube, this demonstrates the use of artificial intelligence with the Baxter, albeit simple.

The vision system used will need to analyse each cube face when an image of each is taken by one of Baxter’s cameras. The colour in each of the nine positions on a Rubik’s cube needs to be determined, and this process repeated for each of the six faces. A total of six colours will need to be differentiated, these commonly being white, orange, green, blue, yellow and red. This vision system should be robust enough to allow for colour variance due to lighting and using different Rubik’s cubes.

Movements made by Baxter robot must allow all the required manipulations. By inspection, a Rubik’s cube has a total of six rotatable faces, and each face can be rotated a quarter, half and three quarters in either direction. The total number of movements required is reduced if we make the quarter and half turns clockwise, and replace the three quarter turn with a quarter turn anti-clockwise. Thus only three manipulations are required per face, totalling 18 manipulations. All these need to be programmed as servo movements in the corresponding arm to achieve the needed rotation. Additionally movements will be needed to pick up the cube from a predefined location, allow all the faces to be scanned, and place the cube back where it was initially. All these manipulations will require the use of both arms, which in turn will require to be well co-ordinated, otherwise the Rubik’s cube could be dropped. Without implementation of a system to detect if the Rubik’s cube is dropped, this would result in Baxter failing to solve the cube.

All the movements must be accurate and repeatable so the same movement results in the same face rotation every time it’s performed. If the movements are not accurate enough then we could either damage Baxter or the Rubik’s cube, along with fail the manipulation, and ultimately the task of solving the cube. Ideally the movements should allow Baxter to work within a realistically small space, and be as smooth as possible. Appropriate movement speeds should be considered, taking into consideration Baxter is designed to be used without a protective cage, and as such movements should not be fast.

The algorithm itself that combines these three aspects should control all of them and require no interaction after being initiated. Proper communication between the aspects is essential to solve the Rubik’s cube. Ideally the algorithm code will be clean, well-written, commented effectively and modular. Modularity will allow the code to be easily maintained, debugged and modified. A clean and commented code will enable others to understand how it works, and what every part is doing.

As an extension to the project, the vision system could be expanded to allow any six colours to be detected, rather than just the six common colours. In addition to this, the ability to solve 4x4 Rubik’s cubes. This would require researching and developing a new solving solution and modifying the vision system to recognise what type of Rubik’s cube is being used. Additional changes to the grippers would be required to allow proper manipulation of the Rubik’s cube. This would need a different gripper configuration, raising the question as to whether the current grippers are optimal, or at least capable of the required manipulations.

**1.3 Significance**

This project will demonstrate how an algorithm that combines a vision system, servo system and motion planning system along with a solving algorithm can be used to complete tasks where more variables are present. By enabling robots to work in a dynamic system, the number of applications robots can be used for increases greatly. This not only aides industry, who require specific working environments for the robots, but also applications where the environment the robot is used within can vary greatly.

By demonstrating more practical uses for artificial intelligence, intelligent automation will become more widely used. This changes robots from following a set of motions to complete a task, to manipulators that use planning to determine the most efficient way to complete a task where the conditions or the task its self is changing.

Finally, this project demonstrates the use of dual arm robotics to perform more complex manipulations. This allows robots to perform many more manufacturing task in industry, allowing the application of the accuracy and repeatability of robots to more complex tasks. Not only does this reduce manufacturing costs, but increases quality and quantity of parts manufactured.

**1.4 Report Organisation**

Presented in Chapter 1 is the introduction. This includes a brief introduction to the current state of art and moves onto introducing the Baxter Research Robot, and finally the project. The project is further developed by exploring the objectives and resulting significance of the project.

Chapter 2 provides an in depth analysis to the current state of art relating to the project along with a literature review on relevant papers.

Chapter 3 develops the project further by discussing the proposed approach to fulfilling the earlier defined objectives.

The current progress towards the project is presented in Chapter 4. This includes an in-depth discussion of all relevant concepts.

Finally, the conclusion is in Chapter 5 and discusses the report as a whole, including the current use of robotics, the project and its objectives, the significance the project will have on the current state of art and the current progress of the project, including the planned development of the project.

1. **Background**

Robotics is used extensively in industrial applications where high accuracy and repeatability is required. By using robots the quality of the product increases along with the speed of production. But industry isn’t the only place robotics is being used. Service applications, military use and space exploration are some of the areas robotics is expanding into. The environment and tasks required by robots is becoming more complex and demanding, resulting in robots that can function in more variable and complex situations (Hajduk, Jenčík, Jezný, & Vargovčík, 2013). In industry this has caused a move from immobile repetition robotics to mobile robots capable of functioning in a spread out workplace, and the addition of sensors allows them to react dynamically to a changing environment. Human co working with robots, Baxter.

Artificial intelligence (AI) has classically been developed separately to robotics. Rather than a missed opportunity, this is probably due to the complexity of developing a truly intelligent AI that thinks like a human. Current implementations of AI with robotics consist of ‘smart’ robotics which are solely focused on the application, and the type of environment characteristic of that application (Bogue, 2014). Well-developed AI exists for learning and reasoning, language, perception and control. As stated by (Hajduk, Jenčík, Jezný, & Vargovčík, 2013), robotics has reached a point where the next developments are focused on increasing intelligence, enabling robots to expand to more complex applications. To use AI in a meaningful application with robotics, it would require combination of aspects in many of the field of AI. This project is focused on only a small area of AI, but by combining vision systems with a simple AI in a robot, it demonstrates that complex tasks that can be completed even with the application of simple AI.

Without the application of AI, industrial robotics has expanded to using multiple robots to perform different tasks, resulting in a complex application (Zhang & Ouyang, 2012). An excellent example of this is welding in automation where one robot will position a piece for the other to weld correctly. Multi robot work cells also allows an increase in speed of completion, where multiple robots can be working on welding a large area, while other robots visually check the integrity of the welds made.

Moving from multi robot work cells to multi arm robots allows redundant controllers (as each robot need to be controlled individually, and then a master controller co-ordinates the two individual controllers) to be removed. This increases mobility while still maintaining some of the benefits of a multi robot system. It also allows robots to perform more like humans, both of which extend the applications available to robots (Zhou, Ding, & Yu, 2011). An example of dual arm robotics can be found in space applications. Development of dual arm space robotic systems is currently achieved by relying on tele-operation from an external location. This requires the same sensory information that could be used by an AI to automate tasks without the need of constant external control. Due to this dual arm robots could be the best choice for adaptation with AI to industrial applications, especially where the task or environment is hazardous to humans. This could lead to much safer workplaces along with decreasing running costs and increasing efficiency while maintaining high quality. Dual arm robots’ simular abilities to humans also makes them an attractive platform for future AI applications when AI has reached a level of sophistication comparable to humans.

* Baxter projects done!! Expand on everything above
* Do the frigging literature reviews, try to get close to 20 (isn’t going to happen)

1. **Proposed Approach**

To more easily analyse the project as a whole, it has been broken down into smaller modular parts. Additionally these are described in such a way that they can be developed separately and combined afterwards. This aids with modifying parts of the project, or in debugging issues, should they arise.

The task of solving the Rubik’s cube has been broken into the following parts; the vision system for analysis of the cube, the solving solution for planning the required manoeuvres to solve the cube, and the arm movements required for picking up and placing the Rubik’s cube along with the required manipulations to be performed on the cube. Using motion planning, the Rubik’s cube will be initially picked up by Baxter and then positioned in front of Baxter’s head camera. The vision system will then take images of each side of the Rubik’s cube and analyse these to determine the colour in each of the nine sections, over the six sides. This information will be sent to the solving solution which will provide a set of face rotations to be performed. These then need to be converted into arm movements using motion planning, and then will be performed. The solved Rubik’s cube will finally be placed back where it originated using reverse kinematics.

The vision system will be developed using OpenCV version 3.0 RC1 (Open Source Computer Vision Library), a computer vision and machine learning library (Itseez, 2015). It provides over 2500 algorithms allowing both visual analysis and machine learning and has C++, C, Python, Java and MATLAB interfaces. The vision system will analyse the Rubik’s cube by taking the input from Baxter’s head camera and processing it using a procedure developed from the algorithms provided by OpenCV. Edge detection algorithms will be divide up the face being analysed into the nine coloured sections, then the colour in each of these sections will be sampled. To determine the colour, the sample could be compared to pre-set ranges defined for each of the common colours. Another method would be taking the sample value, and adding a range to this value. As more colour sections are sampled, its value will be compared to previous sample value ranges. These will be assigned as the same if its value is within a pre-existing range, otherwise it will be defined as another colour, and assigned its own value range. Testing the vision system will determine which method is more accurate. Another possibility would be to use both systems, and compare the results. Again, testing will determine the viability of this solution. To increase the accuracy, checks will be used ensure there is six and only six different colours, and nine of each colour. Additionally each centre colour section will be tested to ensure each is a different colour. If any of these checks fail the whole cube will be re-analysed.

When working with Baxter the Software Developers Kit (SDK) (Rethink Robotics, 2014) will be used. The SDK provides an interface to control Baxter’s hardware through the ROS. The SDK also allows control of ROS using Python through a Python interface. The SDK allows programming control of Baxter enabling direct integration into the developed algorithm. Additionally the ROS tools RViz (Rethink Robotics, 2014) and MoveIt (Sucan & Chitta, n.d.) will be used. RViz is a 3D visualizer that displays sensor data and state information from ROS using a virtual model of the robot. Additional sensor information and camera data can also be displayed while Baxter is moving. MoveIt provides motion planning, kinematics and inverse kinematics, collision checking and trajectory planning.

The solving solution will implement as an algorithm that solves the Rubik’s cube. The arrangement of the colours on the cube will be passed from the vision system to the solving solution, which will then produce a set of face rotations that when performed will result in the Rubik’s cube being solved. These rotations will need to be converted to arm movements to be performed by Baxter. The solving solution won’t be developed as many have already been developed, instead an already created program will be used. Research into the best solution will need to be undertaken and several factors will decide the optimal program to be used, such as interaction with it through Python, speed of solution and compatibility with Ubuntu.

Arm movements will need to be developed, and will use MoveIt to plan the movements themselves. These then need to be implemented into Python code. The movements required includes picking up and placing the Rubik’s cube, orientating each face in front of the head camera allowing images to be taken, and manoeuvers to manipulate the faces of the cube. All these movements will be predefined, and as such the picking up and placing of the cube will require the cube to be placed in the same position every time.

A large portion of the project requires programming, and as such a programming language will need to be used. Python version 2.7.6 (Python Software Foundation, 2015) has been picked as OpenCV, ROS and SDK all have python interfaces, allowing easy of control using Python. Additionally Python was created with code emphasis on code readability resulting in easy to read and write code. Python 2.7 was chosen over Python 3.4 due to more support for version 2.7 and version 3.4 could be incompatible with OpenCV, ROS or the SDK. The Integrated Development Environment (IDE) has changed from Visual Studios to Ninja IDE version 2.7 (NINJA-IDE, 2012). This change was made as Visual Studios does not run on Linux, whereas Ninja IDE does. This allows one operating system (Ubuntu 14.04) to be used when developing and testing the algorithm.

This project requires computer work, and as such a workstation has been set up and directly connect to Baxter. This computer will have both RViz and MoveIt tools, along with Python and Ninja IDE. A second computer, a personal laptop, has been set up to allow development and limited testing while Baxter is unavailable. This computer has been set up to mirror the workstation as well as possible. This ensures programs developed on the laptop will work on the workstation. The simulation software Gazebo (Open Source Robotics Foundation, 2014) will be installed. Gazebo simulates robots with a high accuracy in both indoor and outdoor environments. It provides physics, visualization, programming and graphical interfaces. This will allow testing of the algorithm without having physical access to Baxter. This is especially important as Baxter is being used in multiple projects, and as such time will need to be split to allow testing and access.

1. **Preliminary Results and Discussions**

Cube Explorer 5.12 (Kociemba, 2014), as mentioned in the introduction, has been found as the optimal solving solution. This program is developed by Kociemba to find near optimal and optimal solutions to a Rubik’s cube. The algorithm used to solve the Rubik’s cube is the Two-Phase Algorithm, also known as the God’s algorithm. In (Rokicki, Kociemba, Davidson, & Dethridge, 2013) using the Two-Phase Algorithm it is proved that the God’s number is 20 for a Rubik’s cube, that is all positions can be solved within 20 moves or less in the half turn metric (HTM). The HTM refers to how each face rotation is counted, in this metric a quarter turn clockwise, half turn and quarter turn anti clockwise are all counted as one move each. This is opposed to the quarter turn metric (QTM) that counts a half turn as two moves, as the move is equivalent to two quarter turns. Cube Explorer is designed for HTM, but a QTM version is available. The HTM version will be used as it performs better solving the cube, and there is no advantages to using the QTM version. Expand on the actual program, its interfaces ect.

Although it is possible to find the optimal solution, it can be a lengthy process. A test done generating random cubes and finding the optimal solution, it takes more than 20 minutes to find the list of manoeuvers on the person laptop. A test done by Kociemba in 2009 used Cube Explorer 4.64 to solve 100000 random cubes optimally (Kociemba, 2014). It took on average 17.7 minutes to optimally solve each cube. Additionally in 2010 Tomas Rokicki solved 1 million random cubes optimally. The results are tabulated below.

|  |  |  |
| --- | --- | --- |
| Required Manoeuvers | Percentage of Solutions Kociemba | Percentage of Solutions Rokicki |
| 15 and less | <1% | <1% |
| 16 | 2.7% | 2.6% |
| 17 | 26.7% | 26.7% |
| 18 | 67.1% | 67.0% |
| 19 | 3.3% | 3.4% |
| 20 | 0.0% | 0.0% |

These results indicate majority of cube solutions will involve either 17 or 18 manoeuvres. Unfortunately these results require on average 18 minutes to solve optimally, depending on the computer used. Cube explorer allows

* Cube explorer sub optimal solutions
* Testing came to 20 instant, 19 couple of seconds
* Saving time in manipulations might not make a big enough difference.
* Interfacing with python – sending to local port 127.0.0.1/?blah
* Type of notation needed, need to convert it in python before sending. Receive the messages from it. Settings can be changed to change the number of manoeuvers maximum. Could be less than this.
* Manoeuvers will need to be converted to motions
* Open CV as the vision system
* How open cv handles images, videos are done frame by frame
* Manipulations can be done frame by frame, testing the vision system will determine whether it is better to use video or an image.
* Baxter camera will be mounted as a webcam, accessed that way.
* Currently I can open images, save them, open webcam feed, save videos, ect.
* Possiblily of using an external light source, maybe a usb light plugged into baxter/workstation. Shiny surface on the rubiks cube colours will need to be checked.
* Motion has not been done yet, going through provided tutorials to get baxter to move will be required.
* Tools mentioned will be used.

1. **Conclusion**

* Sum that shit up bro, project, current progress, significance ect.

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