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Restoration of the Baxter Robot for use in Research and Teaching

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Declaration

I confirm that I have read and understood the Plymouth University regulations relating to Assessment Offenses and that I am aware of the possible penalties for any breach of these regulations. I confirm that this is my own independent work.

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Abstract

This paper covers the restoration of the Baxter Robot project at the University of Plymouth, which ended in 2016. This includes an in-depth look into the Baxter robot and surrounding field, which incorporates topics such as teleoperation, robot-human interaction, robotics arms, industrial robotic and domestic-home robotics. As part of the Baxter robot's restoration a replacement end effector has been designed in CAD using Autodesk Fusion 360. The design underwent a series of structural analysis tests in the form of Fusion 360's built in finite element analysis (FEA) simulation software. The FEA testing provided an evaluation of the model which concluded that a suitable model had been produced to endure the full force of Baxter with a safety factor above five; with two different models produced, the material being 3D printed ABS, or machined Aluminium. The project also develops inverse and forward kinematics for Baxter's arms. A simulation in MATLAB is used to show the full range of Baxter's arms in 3D by cycling through joint angles for each of servos. Additionally, a 2D representation can be seen, mapping all of the possible end effector positions of one of Baxter's arms. A model to demonstrate the inverse kinematics is also produced in a MATLAB simulation where the user can input the X,Y coordinates of a target location into the kinematic model which then calculates to joint angles of the servos in order for the end effector to reach its goal. The project also used the Rethink Robotics ROS Baxter robot Gazebo 7 simulation to perform interactive testing with the Baxter robot using the keyboard. Lastly, an interactive programme in MATLAB was used to carry out semaphore signalling, which was used to spell out Baxter, when the user inputted the characters. The paper then concludes that the Baxter robot retains a lot of value for research and teaching purposes and that the project provides a starting point for future projects to continue from.

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Contents

1. Introduction

The overall focus of this project is the restoration of the University of Plymouth's Baxter Robot, which was first manufactured by Rethink Robotics in 2012 (Robots IEEE, 2020a). The University of Plymouth's Baxter robot has been out of use since 2014 and due to researcher's departure and damage sustained by Baxter. The Baxter robot has a damaged end effector which needs replacing and in addition, software needed to be provided to interact with the robot in order for future research to be carried out. Therefore, the overall goal of this project is to restore the Baxter project to the point where research, using the robot can once again take place at the University of Plymouth. In order to achieve this the project was broken down into four objectives.

- Design a replacement end effector for the Baxter Robot
- Have a working model of the Baxter Robot
- Provide working code to interact with the Robot
- Further experimentation

The first objective involves designing a new replacement end effector which can be printed and fitted to the Baxter robots' arm. The main software used in the objective is Autodesk Fusion 360 which is used to create a 3D CAD model of the end effector, and is also used to carry out structural analysis on the model in the form of finite element analysis (FEA) which provided me a level of confidence with my design when experiencing extreme forces. The second objective involves creating an environment with ROS and MATLAB where a physical and mathematical model of the Baxter Robot is present and ready for testing. The ROS element of this objective also involves an instructional document which provides potential future researchers with a way to set up a ROS environment using the Rethink Robotics simulator legacy software on the University's software requirements. For the MATLAB aspect of this objective, the focus is on providing the kinematics of the Baxter robots' arm and the robots parameters. Objective three is focused on using ROS and MATLAB to interact with the Baxter robot. The ROS implementation involves controlling the robot's arms in a Gazebo simulation and the MATLAB implementation to focus on demonstrating the kinematics of the Baxter robot using the MATLAB robotics toolbox. Lastly the fourth objective is to provide additional project ideas and uses for the Baxter robot to be used in future research projects at the University of Plymouth.

Due to the global pandemic of COVID-19, the direction of the project changed from its original objectives. Originally the project was to be more focused on running a full diagnostics test and repair on the University's Baxter robot, followed up with the running of simple physical testing, which would include the robot interacting with the environment around it. However, due to the pandemic and the closure of the University's campus on 16th March 2020, the goals and objectives of the project had to be adapted to compensate not having access to the robot and thus the project moved towards a theoretical and simulation based project, which places a greater emphasis on the literature and fields surrounding the Baxter robot.

Throughout the project, careful planning and management took place using a series of Gantt charts which allowed me to breakdown all my work packages into smaller, more manageable tasks. Over the duration of the project three iterations of the Gantt chart were produced. The original Gantt (Appendix 1), was produced pre-Covid-19 and outlined my original project plans before the University's closure. Upon the closure of campus, the project plan was revaluated to match the new direction of the project. The new Gantt chart removed several tasks from the project plan as with the project being mainly theory based, some of the tasks were no longer possible and due to the circumstances, some tasks were no longer able to be realistically achieved within the time frame. In addition, the deadlines for work packages were pushed back by a week, due to unforeseen deadlines changes for semester two which meant that I started working on the project a week later than expected (Appendix 2). In this update of the Gantt chart I also changed how I staggered some of the tasks, by setting some tasks to run over a longer period in parallel to other tasks. This adaptation was made to allow me to work on related tasks simultaneously, which in practice helped greatly when it came to problem solving. The finial iteration of the Gantt chart is seen in (Appendix 3), which is updated due to the change in deadline, which allowed for a final adjustment of remaining tasks to be completed. The final Gantt chart is also a representation of how the project played out, rather than a forecast and therefore lends itself as a way to evaluate, time and project management skills, throughout the duration of the project.

The code for both the MATLAB and the ROS simulations that were carried out during the project can be found on the projects GitHub repository, along with video demonstrations and CAD files: https://github.com/bwickenden/PROJ509_Baxter_Restoration_Project.git Documentation on the project was also kept locally as well as on the OneDrive. The ROS simulations were carried out in a virtual machine boot of Ubuntu 16.04, using ROS Kinetic. In addition to formal documentation I also kept a paper journal which was used to planning tasks, note taking, rough mathematics and evaluation at the time of experimentation.

2. Literature Review

Abstract

In this literature review I will be looking into the current applications and research areas in relation to the Baxter robot focusing on areas of research and for teaching purposes. Following this, an analysis into the field surrounding the Baxter robot is carried out, starting with what other robots and robotic arms are available, that are within similar fields and scope of the Baxter robot. This paper then leads into an in-depth look into the field of home robotics and how some applications could help to tackle issues that come about due to a pandemic. The topics discussed include: Care robots, cooking robots, robot-human interaction and work from home robots, with each being linked to how they could apply to Baxter. The paper concludes that Baxter, whilst old, is yet to become obsolete, due to the assortment of hardware which allows him to be used to carry out research into robots working within the same environment as humans, in addition to his more traditional tasks.

Introduction

My research project is based upon the restoration of the Baxter robot that is currently at the University of Plymouth. The Baxter robot is designed to for a variety of purposes including object identification, light assembly, material handling. The Baxter robot has two industrial robotic arms with 7 degrees of freedom each, with compliant joints which have force sensing capabilities, a 360^{o}-sonar detection sensor, and 3 cameras (Rethink Robotics, 2012). With this assortment of sensors and actuators the Baxter robot has a large variety of potential capabilities. The robot has the potential to be used in research areas ranging from object identification, pick and place, human interaction, robotics in a home environment, robot-human interaction, machine learning and many more.

A feature that makes the Baxter robot interesting is that it's been designed to operate in an environment without a protective cage around it. Most industrial robotic arms need to be out of reach of humans and confined within their own personal workspace. As part of the Baxter robots design, they implemented a system which utilises its force sensing ability, series elastic actuators, and cameras to detect or prevent robot-human collisions (Fitzgerald, C. 2013). With this ability it places the robot in an unusual category as it has the potential to be used in home like environments, whilst still having the capabilities of an industrial robotic arm. With research into home robotics increasing in popularity, the Baxter robot could be used to investigate the viability of cooking, cleaning, and other domestic tasks.

With the Baxter Robot being first produced in 2012 by Rethink Robotics (Robots IEEE, 2020a), the Baxter has been involved in many research projects since. One of the projects involved an advanced telecommunication system using an MYO armband which has 8 inbuild EMG sensors accompanied by a 9 axis IMU, to allow the user to control the Baxter robot with the movements of their own arm (Yang, C. et al. 2016). Additionally, another project made use of a mobile robot to further increase the safety of the environment when the Baxter is operational. The research team created a warning system which implemented an Xbox Kinetic camera sensor on the mobile robot which would survey the area within the Baxter's range. When a human gets closer to Baxter, it would alert them that they have crossed one of the three thresholds of safety ranging from safe (+3m), caution (3m), danger (1.5m), and emergency stop (1m) (Reardon, C. et al 2015). Despite the robot now approaching 8 years old the Baxter robot is still being used in research projects and has a lot of potential as a tool to pioneer modern day robotics which is explored throughout this paper.

Industrial robots

In recent years Rethink Robotics have developed the successor of the Baxter Robot, named the Sawyer Robot, which was released in 2015 (Robots IEEE, 2020b). The Sawyer robot has a singular industrial robotic arm with seven degrees of freedom and has two integrated cameras, along with built in force sensing capabilities (Rethink Robotics, 2019a). Sawyer is designed to carry out pick and place tasks as well as specific manufacturing task such as CNC machining, injection moulding, circuit board assembly, and packing, along with many other tasks (Rethink Robotics, 2019b). With Sawyer's force sensing capabilities, it allows Sawyer to carry out tasks carefully, by monitoring both the torque and position of each of its servos individually and simultaneously (Rethink Robotics, 2019c). By doing this it allows the robot to monitor and control the amount of force that it is applying to its target. With this ability, the Sawyer robot is able to carry out tasks within a sensitive environment, where a regular industrial robot arm, without force feedback capabilities, would not be able to operate within safely. This is a similar trait that the Sawyer robot shares with its predecessor, the Baxter robot, that also made use of compliant joints with force sensing, which allowed it to operate within its environment with increased levels of safety (Rethink Robotics, 2012). One of the big ways in which the Sawyer robot is not similar to the Baxter robot is that the Sawyer robot is less bulky and is instead flexible and streamlined to enough to work in environments which may be difficult for its human counterparts to operate within (Rethink Robotics, 2019a). This is achieved with the application of Rethinks Robotics' Inertia Software and advanced embedded vision system, which allows for the Sawyer robot to reorient its position into a dynamic pose to suit the operational environment (Rethink Robotics, 2019b).

Another example of an industrial robotics arm which is designed to work alongside its human counterpart within the workplace environment is the LBR iiwa robotic arm developed by KUKA which was first released in 2013 (Robots IEEE, 2020c). Much like the Baxter and Sawyer robot the LBR iiwa robot also makes use of compliant joints with torque sensors, which measure any external forces that are acting on the robot to prevent injury to itself and others. This is to once again ensure safe operation when around humans, also making sure that the force being exerted by the robot is appropriate for the task at hand, as the robot may be operating with delicate or dangerous materials (KUKA, 2017). Similar to the Baxter and Sawyer robots, LBR iiwa is also capable of carrying out complex tasks including but not exclusively: machining, inspection, assembly, as well other tool task such as paining and gluing surfaces (KUKA, 2020). In addition, the LBR iiwa robotic arm also has the ability to attach a variety of media flanges which allows the robot to interact with its environment in diverse ways. This includes electric/IO/touch/inside electric media flange, pneumatic/IO/touch/IO valve/inside pneumatic media flange, and the basic flange. With a large variety of media flanges, the LBR iiwa robot is able to carry out a large number different and distinct tasks, but it also allows the user to interact with the robot in a versatile way (KUKA, 2017).

Robot-enhanced Home Automation

With the Baxter robot being designed to operate within an environment without being placed within a safety cage, research can be carried out using the Baxter robot to further develop the field and our understanding of areas such as human-robot interaction and home robotics (domestic robotics). Safe interaction between robots is becoming increasingly important with more robots and robotic devices being in consumer home than ever before (Sahi, M, 2020). With advancements in the field of home robotics, robots are now able to carry out tasks and services which would have previously required a person to carry out. This is now, more important than ever during the COVID-19 pandemic, where social distancing has become a key and important part of everyone's lives for a prolonged period of time. During the pandemic mitigating the amount of people that you come into contact with and interact with is essential for the safety yourself and others around you. With the application of home robotics, in areas such as care, cleaning and cooking. Additionally, robots could be used to allow users to carry out their jobs from the safety of their homes during the current pandemic via teleoperation.

I. Care Robots

The need for care robots in the future has been identified by governing bodies around the world, such as the United Kingdom's government, which predicts by 2040, around a seventh of its population will be aged 75 or over and that they have identified that autonomous care robots are part of the solution to providing the nation with effective care (Department for Business, Energy & Industrial Strategy, 2019). One of the robots that the Government of the United Kingdom recognised as an already suitable robot to carry out care activities and responsibilities is the Pepper robot, which is a humanoid robot created by Softbank Robotics (Robots IEEE, 2020d). The Pepper robot is designed to be a social robot, with robot-human interaction being its primary feature, with Pepper having speech recognition for 15 languages, and a perception module which allows Pepper to recognise and interact with people. In addition, Pepper has a total of 20 degrees of freedom which allows it to carry out expressive movements which look natural (SoftBank Robotics, 2020b). Within the care industry Pepper could fulfil a role as a robot companion, with the use of its' social abilities which allows it to communicate positively to patients in care, whom may spend extended duration of time alone (SoftBank Robotics, 2020c). Also, Pepper can assist patients to self-diagnose health issues and can be used to monitor and track on going health issues (SoftBank Robotics, 2020a). By having a robot such as Pepper carry out assistive medical care, medical staff are required for fewer visits or a shorter period or time for simple, but time-consuming tasks can be offloaded to an autonomous robot. With the use of teleoperation, carers and medical staff can also operate the Pepper robot to carry out telemedicine tasks, which allows them to interact with the patient remotely and due to Peppers interactive chest display, which allows for visual interaction(SoftBank Robotics, 2020b) (SoftBank Robotics, 2020a).

Another example of a care robot is the Robear which is another humanoid robot designed to be used in a care situation (Riken, 2015). The main use for Robear is to assist patients who are for example wheelchair bound to move between their chair and their bed (Gallagher, A. et al., 2016) (Johnson, M.J. et al., 2017). The Robear has two robotics arms which it uses to perform a lift action upon the patients and utilises torque sensors alongside capacitance-type tactile rubber sensors which allows for the robot to interact with the patients safely, without causing harm (Riken, 2015). Whilst the Robear robot cannot work autonomously and does require the aid of carer or medical professional, it does allow for the patient to be moved with ease without the need for the carer to exert themselves, especially if the patient requires to be moved on a regular basis.

II. Cooking Robots

With it becoming more normal for robots to carry out menial tasks within the household, we can now start to see the idea of having a cooking robot that can autonomously prepare and cook meals within a household. By having a cooking robot installed within the home it could allow for people who live busy lives to be able to still eat nutritional and healthy food, without the time commitment required to usually cook meals. Also, a home cooking robot could also benefit someone who is not able to cook due to illness, health related issues and the elderly. With many countries, such as Japan (Wada, K. et al., 2013) now having an aging population, allowing the elderly to maintain their independence is going to become an essential part of the future and having cooking robots to allow them to have healthy home cooked meals prepared for them could be part of the solution (Ma, W.-T. et al., 2011), (Pearce, A.J. et al. 2012)

An example of a home cooking robot is the robot kitchen designed by Moley Robotics (Moley Robotics, 2020a). Moley's robot kitchen is comprised of a workstation which contains a stove, oven and food prep area, which the robotic arms can interact with autonomously. The robot kitchen makes use of a library of recipes which it can cook, when the given ingredients are provided and placed within the correct areas. The robot kitchen also has an option for the user to create their own recipes for the robot to re-create. This is achieved by making use of a 3D camera which tracks and records the user's skeletal kinematics whilst they cook, which can then be later replicated by the robotic arms. In order for the user to interact with the cooking robot an interactive touch screen is provided as part of the workstation, as well as a mobile application which allows the user to interact with the robot kitchen (Moley Robotics, 2020b). A similar example of this style of cooking robot can be seen produced by companies Samsung, with their Bot Chef, which works as a kitchen assistant alongside other human chefs (Samsung Newsroom, 2019) (Teachable, 2019).

Connected Robots is another company that has been developing several robots to carry out a variety of tasks within the kitchen. Their list of robotic systems include the following: OcotChef A robot designed for baking), Soft Cream Robots (An ice cream serving robot), HotSnack Robot (A fast-food cooking robot), Lorine (Which is a breakfast robot), Dish Washing System I (A cleaning robot), Dish Washing System II (Cleaning), Dish Washing System III (Cleaning), Beer Serve Robot (Serving Robot), Soba Robot(Designed to cook and serve food at train stations), and Chef Collaboration (Which is an assistant chef robot) (Connected Robotics, 2015). All of the robots designed and created by Connected Robots have been designed to work alongside their human counter parts, with the goal to offload the workers from repetitive, low skill tasks, this is achieved by using 3D cameras with the implementation of AI and machine leaning.

In a research study carried out by Zhai, J. et al., (2015) they simulated a dual arm, 6 degree of freedom robot to carry out Chinese cooking methods, with the idea of providing quality dishes autonomously, without the need of a master chef. In the paper, they focus on the action required to flip food within a wok, which is achieved with the use of inverse kinematics and dynamic equations, which are provided by the Lagrangian method, which calculates the Kinect and potential energy of the arms. Another research study carried out by Inagawa, M. et al. (2020) proposes a method of recipe analysis which involves turning a cooking recipe into a series of motion codes, which can be used to control the robot. The study finds that by using a data base of motion codes, the robot is able to pick out key words within a recipe and carry out the required action autonomously. However, the database that the robot uses is complex and needs simplifying for further research and operation. Lastly, we can see that in a study ran by Petit, A, et al., (2017), they were able to train a robot to make a pizza. This was achieved by using an RGB-D 3D camera to create a point cloud, which enables the robot to track elastic deformable objects that are textured, such as pizza dough. The unique aspect of this research is that unlike other research projects this deals with handling non-rigid objects, whereas most research appears to be in the handling of rigid tools.

III. Teleoperated Robots

One example of using robots to work from home is a company in Japan called OryLaboratory, which has created a service robot that can be remotely controlled named the OriHime robot (OryLabortatory, 2020). In 2018 OryLaboratory conducted a trial in a café in Tokyo called Dawn Ver Café, where the service was provided by robots controlled by people with disabilities which prevented them working, with the goal of allowing them to remain (independent Steffen, 2020). The OriHime robots were teleoperated from the homes of the workers, where they could control the robots to collect table orders, and to deliver the customers food and drink. The robot interface to control the OriHime robots has been designed to be interactable for people who have ALS and are paralyzed, which is achieved by the use of eye control, body language and simple gestures (OryLabortatory, 2020), (DAWN, 2020). Since the trial which took place in 2018, the fast good giant MOS Burgers is now currently undertaking a new trial using the OriHime robots to allow their workers which cannot commute due to illness, to continue working (Baseel, 2020). In a paper written by members and founder of OryLaboratory (Takeuchi, K. et al., 2020) they concluded that their studies had shown that the interactions that the patients had with the robot avatars whilst working, has had a positive effect to their mental fulfilment. Additionally, the paper finds that by providing people who require care an opportunity to continue working from their homes, it allows them to remain within a care environment, whilst maintaining their independence.

Another company that is trying to pioneer the robot aided work from home industry is TELEXISTENCE, which has designed the Model H robot (TELEXISTENCE, 2018). The Model H robot is a mobile humanoid robot which has been equipped with stereo cameras, binaural mics, and haptic sensors. The robot is controlled by teleoperation by the user, which interacts with the robot using the cockpit that is provided. The cockpit is an all-in-one station which includes a virtual reality (VR) headset, Haptics gloves and display which allows the user to interact with the robot over long distances, from the robot's perspective (TELEXISTENCE, 2019). With the use of the VR headset alongside the haptics gloves, the user is able to control the robot's arms to interact with its environment, whilst being provided physical feedback. The robot uses a hybrid method of control where it takes the uses inputs movements in combination with an AI to best optimise the task at hand, which assists in tasks such as pick and place and grasping objects. For versatilely the robot can be connected to via variety of methods including Wired LAN, Wi-Fi, and via a mobile network, which allows the robot to be used in diverse environments (TELEXISTENCE, 2018). For example, the robot could be used to carry out dangerous task, which may pose a physical or environmental hazard to humans, however for a task of great severity a wired connection may be preferred if the robot is not required to travel any great distance and is perhaps stationary. However, on the other hand, if the robot is being used for social activities where the robot may be moving around traversing its environment, then connection over the Wi-Fi or mobile would be more appreciated, especially for longer distances.

Robot-Human Interaction

The GummiArm is a soft-robot arm developed at the University of Plymouth by Dr Martin Stoelen and is designed as an open source project with the idea that anyone could 3D print the parts from home and to assemble the arm themselves (Stoelen, F, M. et al., 2018). The GummiArm is designed to be safe for robot-human interaction and makes use of soft robotic applications to allow for both the user and the robot to remain safe when interacting with each other. The GummiArm achieves this by using agonist-antagonist joints in conjunction with a duel phase ballistic-feedback controller which allows the hand to react to sensory feedback at high speeds, which was inspired by human ballistic reactions to a sensory input (Stoelen M, F. et al., 2016). This then allows for the arm to have variable stiffness actuation which allows for the arm to dynamically adapt to the external forces within its environment when interacting with objects or people. Not only does this protect the people around the robot, but it also projects the servos which are used to drive the robot from external forces which could damage the gears within. With the use of variable stiffness, research was able to be carried out where the GummiArm would provide shake the users hand and offer a rating for their handshake (Stoelen, F, M. et al., 2018). Another experiment carried out using the GummiArm using a Convolutional Neural Network (CNN) would be able to learn to provide a high five to a variety of users (Denoun, B. et al., 2016). In addition to robot-human interaction the GummiArm has also been heavily modified to be applied to horticulture, where the arm has been used to harvest cabbages and raspberries (Klein, F.B, et al., 2019).

In a study carried out by Li, C. et al., (2020) they used force sensing with a KUKA LBR iiwa robotic arm to provide a massage to the user. The idea behind the project was to provide the service without the need of a person being present and to design a system that would allow for the robot to provide the massage dynamically to suit different users. With the robot being able to autonomously complete its tasks without being controlled by another person, it allows for the robot to be applied to a home robotics setting, such as a smart home. Whilst providing the benefits of having a massage available to the user whenever they chose, without time constraints, within the context of the COVID-19 pandemic, this is another way in which people could continue to social distance and minimise their contact with others. Whilst a massage for many is a luxury, for some people it may be required due to healthcare reasons and therefore this provides an important solution to provide this service.

Modelling Baxter

In a study carried out by Smith, A. et al (2016), they developed a dynamic model from the Baxter robot using the Lagrange formulation. The dynamic model was used to provide the relationship between the torque of the joint actuators and the resulting motion of the joints. The torque of each joint is estimated using Baxter's compliant joints, by measuring the spring deflection using hall effect sensors. The Lagrange-Euler formulation was then used to model the motion of the Baxter arm. With the dynamic model created, an experiment was conducted where one of Baxter's arms was driven through a series of generated trajectories, which concluded that the system was accurate when compared to the real dynamics.

Discussion

With Baxter being a stationary robot, it is not able to perform some tasks such as a lift assist robot like Robear (Riken, 2015). However, with the use of his compliant joints, Baxter is able to work alongside its human counterpart (Rethink Robotics, 2012), Baxter is still relevant for research purposes and can be used to investigate many of the key aspects required to carry out each one of the tasks within the field discussed. In a care related field Baxter has the ability to be expressive with the use of his display screen which is attached to Baxter's head, which would allow him to simulate emotions with eye movements in a similar way to which Pepper is able to when interacting with users. Whilst Baxter's arms are not as complex as Peppers, Baxter still has the capability perform simple emotes with them, when interacting with others. Additionally, Baxter could be used to pass objects to patients who are bound to a bed or wheelchair.

The field of cooking robots is perhaps more suited to Baxter than care, as robots designed to cook often don't require movement around the environment and are usually stationary. With the use of the cameras and torque measurements Baxter could be used in a cooking environment. The RGB-D cameras can be used in combination machine learning, to carry out object identification, which would allow Baxter to identify cooking equipment, such as a knife and chopping board, as well as ingredients such as an onion. Baxter could then carry out a slicing action, whilst using his torque measurements and compliant joints to ensure that the correct amount of force is being applied. This could be especially useful when interacting with more delicate foods such as eggs or meringues. Additionally, similar skills could be transferred to other cooking utility tasks such a washing, cleaning and tidying.

Similar to research carried out with the KUKA LBR iiwa arm (Li, C. et al., 2020), Baxter can use his joint torque control alongside his compliant joints to be used to perform interaction with a human user. In the same way that the KUKA LBR iiwa arm is able to provide a massage for a user, an adapted method could also be applied to Baxter, to allow him to carry out the massage task. Whilst Baxter does not have a complex end effector such as the hand seen on the GummiArm, Baxter can still provide the actions of a hand shake with its arm, Baxter can also be used to pass objects directly to a user's hand, and perhaps with the use of computer vision and machine learning it would be possible to even have Baxter interact with the user in a social setting such as a game of chess.

Due to Baxter being able to be controlled by means of teleoperation, Baxter could be used to carry out research that would investigate was to allow workers to work from home. Teleoperation allows the user to operate the robot remotely, which allows the robot to be used in situation that are not safe for humans. An example of this could be within a lab working with hazardous materials. This could also allow people to work from home in situation such as a pandemic, where social distancing is essential.

It's clear that whilst some progress has been made to create autonomous home robots, there is yet to be a non-specialised robot that is capable of completing a variety of tasks within the home. Further research into machine learning and neural networks is still required to provide a solution for a dynamic home robot. Whilst robots such as Baxter, Sawyer and Pepper are already able to interact with objects and people relatively safely, the software is the constraint that needs to be further developed in order to increase the functionality of the robots. Therefore, Baxter is still applicable as candidate alongside his successors and in some cases may be more suited than Sawyer, due to having two arms.

Whilst the focus of this review has leant towards the application of robots within a home environment to show the potential versatility of the Baxter robot, Baxter is still a credible robot to research industry-based tasks, and many go hand in hand with the main principles behind the home robotics application, with examples being the use of computer vision for object identification and pick and place based tasks. A task involving the use of tools in an industry background isn't vastly different to using kitchen equipment in practice.

With the Baxter robot available at the University of Plymouth, it can provide the equipment and resources that could be used to investigate and research into all the fields discussed. In relation to teaching, it would provide students with an example of human-robot interaction and designing application to work alongside humans. Additionally, it will provide a resource for students to learn about computer vision, machine learning, ROS programming, MATLAB simulations, Kinematic, teleoperations and others. Whilst other robots at the University can be used to apply some of these teachings, few robots at the University can apply all of them and thus the Baxter robot will add value.

Conclusion

After looking into several fields of robotics within the both the industry and home setting, my literature review concludes that Baxter is still a viable robot to pioneer research into all of these fields. Whilst Baxter is some 8 years old (Robots IEEE, 2020a) and is now considered a legacy robot with the release of its successor, the Sawyer robot (Robots IEEE, 2020b), Baxter is yet to become obsolete. Due to Baxter's ability to work alongside it's human counterpart and having an interactive display, Baxter is a versatile robot which allows it to be multidisciplinary in the fields that it can be applied to. Whilst most current applications of the Baxter robot are focused on industrial tasks; Baxter is also suited to home robotics applications. With the market for robots within the home and industry growing the Baxter robot will be a useful asset for the University of Plymouth for both teaching and research purposes. It is also clear that more research needs to be developed and driven by academics to ensure that knowledge and technology is shared and not retained by individual companies.

3. Theory

3.1 Inverse Kinematics

Inverse kinematics is a method of describing the pose of a robotic arm derived from the target position. The main concept of inverse kinematics is that if the coordinates of the target location are known, and the parameters of the robot's arms, in this case Baxter's arms, also being known, then you can calculate the angles of the joints in order to reach the target position. This method is very useful in a simulation environment as the distance and coordinates to objects and target locations is easy to obtain, however in a real-life scenario Inverse kinematics can be difficult to implement and rely on application input analysis such as computer vision and SLAM. In situations where it may be difficult to obtain a useful map of the environment, forward kinematics may be more appropriate. Forward kinematics is a method of calculating the pose of the robotics arms end effector when provided with a set of angles for each joint, which is used later in the project to carry out a series of experiments.

For the inverse kinematic model, I've first focused on solving the 2D kinematics for one of Baxter's arms (Yan, C., 2020) To simplify the kinematic model, we can set the orientation of the end effector φ, which will be equal to the sum of angles (Equation 1). Whilst this does simplify the model and thus limits the workspace of the Baxter robot, Baxter is still able to operate in a large area however the orientation of the arm is restricted to a 2D plane. By using a simpler inverse kinematic model, it allowed for the focus of the MATLAB simulations to tangible, with only one solution to the robots pose being provided, opposed to the serial possible solutions if the robot was not restricted to a 2D plane. Additionally, for the angle of S_2 (equation 3) the positive angle was always chosen to further simplify the kinematic model to, always only provide one solution for the pose of the arm to reach the desired target.

Angles θ_1, θ_2 and θ_2 represent the joint angles of S1, E1, W1 respectively, with lengths a_1, a_2, and a_3 are the lengths of each section of Baxter's arms [table 1]. Symbols c and s represent cos and sin functions of angles θ_1, θ_2 and θ_2 as denoted by subscript. X represents the target, where P_x and P_y are the target coordinates in the x and y axis.

End effector orientation

$$\phi = \theta_1 + \theta_2 + \theta_3 \tag{1}$$

The 2D kinematics are stated in equation 2.

$$X = \begin{bmatrix} P_x \\ P_y \\ \varphi \end{bmatrix} = \begin{bmatrix} a_1 c_2 + a_2 c_{12} + a_3 c_{123} \\ a_1 s_1 + a_2 s_{12} + a_3 s_{123} \\ \theta_1 + \theta_2 + \theta_3 \end{bmatrix} \tag{2}$$

For θ_2 in the frame of w (origin)

$$P_{wx} = P_x - a_3 c_\varphi = a_1 c_1 + a_2 c_{12} \quad \textbf{(3)}$$

$$P_{wy} = P_y - a_3 s_\varphi = a_1 s_1 + a_2 s_{12}$$

$$P_{wx}{}^2 + P_{wy}{}^2 = a_1{}^2 + a_2{}^2 + 2a_1 a_2 c_2$$

$$c_2 = \frac{P^2{}_{wx} + P^2{}_{wy} - a^2{}_1 - a^2{}_2}{2a_1 a_2}$$

$$s_2 = \pm\sqrt{1 - c^2{}_2}$$

$$\theta_2 = Atan\,2(s_2, c_2)$$

For θ_1 in the frame of w (origin)

Substitute θ_2 equation 3

$$s_1 = \frac{(a_1 + a_2 c_2) P_{wy} - a_2 s_2 P_{wx}}{P^2{}_{wx} + P^2{}_{wy}} \quad \textbf{(4)}$$

$$c_1 = \frac{(a_1 + a_2 c_2) P_{wx} - a_2 s_2 P_{wy}}{P^2{}_{wx} + P^2{}_{wy}}$$

$$\theta_1 = Atan\,2(s_1, c_1)$$

For θ_3 in the frame of w (origin)

$$\varphi = \theta_1 + \theta_2 + \theta_3 \quad \textbf{(5)}$$

$$\theta_3 = \varphi - \theta_1 - \theta_2$$

Now that we have solved the kinematics within a 2D plane for the Baxter robots' arm, we now need to solve the kinematics in 3D space. This can be achieved by having the Baxter robot align itself with the same plane as the target using a rotational matrix. This will we achieved by calculating the angle of the target between the x-axis and the z-axis which can be seen in figure 1 (Equation 6). In the code this value is represented by Z0 and is used for the angle of S0.

$$Z0 = atan2(x, z) \quad \textbf{(6)}$$

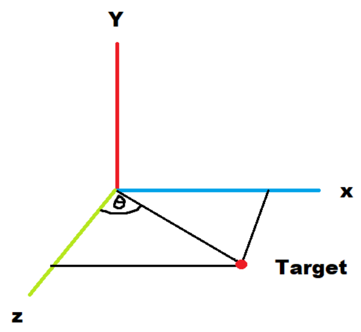

Figure 1: Calculating the Angle for the Shoulder Yaw Joint

With the inverse kinematic model completed, I then continued to run a series of tests using MATLAB's robotic toolbox to visually represent the inverse kinematics generated (MathWorks, 2020b). Firstly, the inverse kinematics are calculated in the vars.m program, using the desired X, Y coordinates, which are the variables Px and Py. In vars.m the parameters of Baxter have been defined using the Rethink Robotics Baxter Manual to declare the lengths of each section of Baxter's arms in mm (Rethink Robotics, 2015b). Once the angles of S1, E1, and W1, (which are represented by b1, b2, and b3 respectively within the code), have been calculated they are then fed into Inverse_Kinematics.m. Inverse_Kinematics.m uses the rigid body tree for Baxter provided to the tool box by Rethink Robotics (MathWorks, 2020a), which is used to visualise the pose of the Baxter robot that the inverse kinematics have computed. The function "targetJointPosition" is used to provide the robot with the inputs for all of the arm's joint angles. In figure 2 I have the input of S1, E1 and W1 represented by the angular outputs calculated in vars.m (b1, b2 and b3). The rotational joint values of Baxter's arm, S0, E0, W0 and W2 are defined in figure 3 and are used to set Baxter's initial pose, where his arms are able to operate without collision with the rest of his body.

```
% Set up joint control targets
%Inverse Kinematics
targetJointPosition = [2*pi S0 b1 E0 b2 W0 b3 W2 pi pi -pi/2 pi/4 pi/2 2*pi pi/2 ]';
show(robot,targetJointPosition)
```

Figure 2: Inputting Inverse Kinematics into Baxter Model

```
S0 = pi/4;
E0 = 0;
W0 = 0;
W2 = 0;
```

Figure 3: Baxter Joint Angle Pre-sets

With the test environment set of within MATLAB, I recorded a data set containing the angles of the joints S1, E1, and W1 for incrementing Px coordinates starting from 300, incrementing by a 10 until reaching 500. For this test Py remained as the value of -300 and the start and end positions are shown in figure 4. As shown, the inverse kinematics were able to successfully move the end effector along the x-axis, to the new target coordinates. The pose shown in figure 4 is one of two possible solutions as the arm could have also take the inverse route, however for this simulation I have simplified the math, which ensure that the robot always takes the positive route rather than the negative.

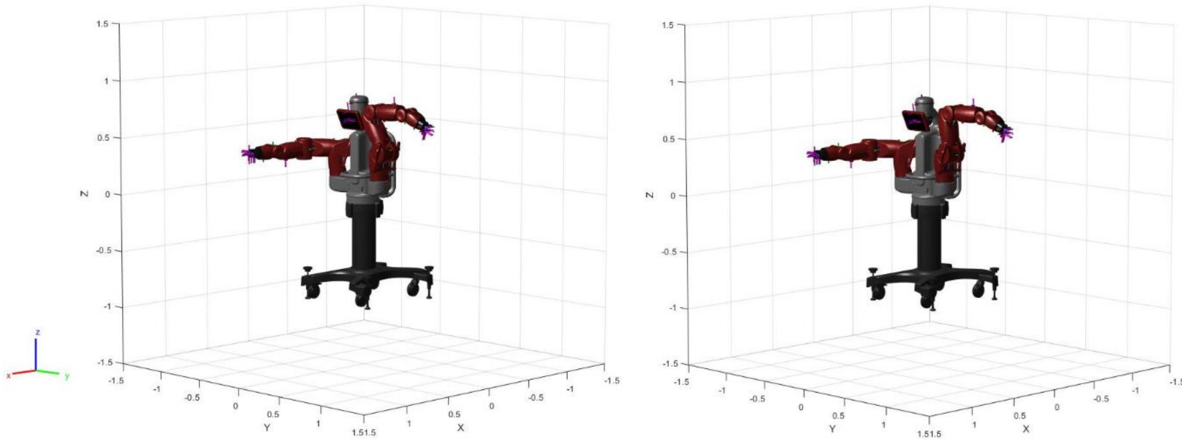

Figure 4: Inverse Kinematics start pose (left), finish pose (right)

3.2 Forward Kinematic

In addition to the inverse kinematic model I've also developed a forward kinematic model. The main difference between inverse and forward kinematics is the control inputs. For inverse kinematics the user would input the target location and the model will produce the values for the joint angles for the pose of the robotic arm to position its end effector within the target location. Forward kinematics allow for the user to select the joint angles of the robotic arm as the input controls, where the kinematic model is then used calculate the pose of the robot and the resultant location of the end effector within the environment. In figure 5, I have used MATLAB using the robotics toolbox (MathWorks, 2020b) to calculate all of the possible positions of the end effector within Baxter's workspace using forward kinematics, where (0,0) represents the base Baxter's shoulder from a side on view, with the front facing to the right. Here it can be seen that Baxter's workspace is mainly directly in front and above its origin; with some positions allowing it to operate behind it. This shows that Baxter is more suited to operating within the environment directly in front of it and would require rotating in order to better interact with the environment behind it. Additionally, we can also see that Baxter is able to interact closely with it the environment in front and above it, however the minimum range of Baxter increases once the end effector passes 0 on the X-axis. Whereas the minimum range of the end effector increases Baxter is still able to operate directly below him and can reach areas further behind him when the location of the end effector is operating below the X-axis, in comparison to when operating above.

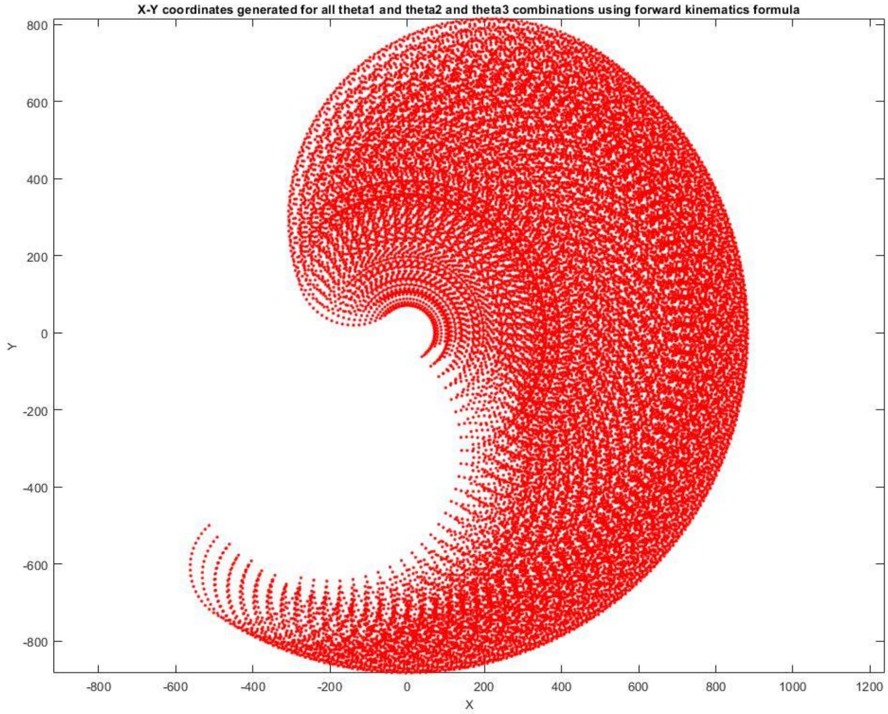

Figure 5: Kinematic Range of Baxter Arm

In the programme, I implemented the parameters of Baxter's arm and set the joint angles of S1, E1, W1 to step through the entire movement range of their values as seen in figure 6 and save them into an arrays called theta1, theta2 and theta3 respectively.

```
theta1 = -2.147:0.1:1.047; % all possible theta1 values %S1
theta2 = -0.05:0.1:2.618; % all possible theta2 values %E1
theta3 = -0.5707*pi:0.1:2.094; %all possible theta2 values %W1
```

Figure 6: Stepping through all values of theta

With the entire range of the angles for S1, E1 and W1 saved into arrays I then calculated the X and Y coordinates of the end effector for every arrangement of angle values figure 7, where the values of l1, l2 and l3 are the lengths of each section of the arm. I then created an array for each one of the X, Y, theta data sets, called data1, data2 and data3; which were then plotted onto a graph (figure 5). All of the parameters of the Baxter robots' arm where from Rethink Robotics Baxter manual (Rethink Robotics, 2015b) and can be seen in table 1.

```
[THETA1,THETA2,THETA3] = meshgrid(theta1,theta2,theta3); % generate a grid of theta1 and theta2 values

X = l1 * cos(THETA1) + l2 * cos(THETA1 + THETA2)+ l3 *cos(THETA1 + THETA2 + THETA3); % compute x coordinates
Y = l1 * sin(THETA1) + l2 * sin(THETA1 + THETA2)+ l3 * sin(THETA1 + THETA2 + THETA3); % compute y coordinates

data1 = [X(:) Y(:) THETA1(:)]; % create x-y-theta1 dataset
data2 = [X(:) Y(:) THETA2(:)]; % create x-y-theta2 dataset
data3 = [X(:) Y(:) THETA3(:)]; % Create x-theta3 dataset
```

Figure 7: Computing X Y coordinates and datasets

Joint	Type	(Radians) Min limit	Max limit	Range	Length between joints (mm)
S1	**Shoulder Pitch**	**-2.147**	**+1.047**	**3.194**	**364.35**
E1	**Elbow Pitch**	**-0.05**	**+2.618**	**2.67**	**374.29**
W1	**Wrist Pitch**	**-1.5707**	**+2.094**	**3.6647**	**144.895**
S0	**Shoulder Yaw**	**-1.7016**	**+1.7016**	**3.4033**	**N/A**
E0	**Elbow Roll**	**-3.0541**	**+3.0541**	**6.1083**	**N/A**
W0	**Wrist Yaw**	**-3.059**	**+3.059**	**6.117**	**N/A**
W2	**Wrist Roll**	**-3.059**	**+3.059**	**6.117**	**N/A**

Table 1: Baxter Parameters (Rethink Robotics, 2015b)

With the range of each of the joint angles being defined, I carried out a simulation, called Forward_Kinematics.m, where I moved each one of the Baxter robots' joints between its maximum and minimum joint angle individually, in the order listed in table 1. The animation shows the full range of the Baxter robot within 3D space and is controlled by inputting the angles for each of the servos individually to move the end effector. The simulation initialises with having the Baxter robots' arms being set to a pose where both arms are facing forward whilst being outstretched figure 8.

```
S0 = pi/4;
S1 = 2*pi;
E0 = 0;
E1 = -0.05;
W0 = 0;
W1 = 0;
W2 = 0;
```

Figure 8: Initialising joint angles

From the initial pose I then set the joint angle for S1 to its minimum angle and then stepped through the entire range of the joint incrementing by 0.1 radians until achieving the maximum value figure 9.

```
for s1 = 0:-0.1:-2.147
  s1
% targetJointPosition = [2*pi S0 s1 E0 E1 W0 W1 W2 pi pi -pi/2 pi/4 pi/2 2*pi pi/2 ]';
  targetJointPosition = [2*pi S0 s1 E0 E1 W0 W1 W2 S0 s1 -E0 E1 W0 W1 W2 ]';
show(robot,targetJointPosition)
 pause(0.2);
end

for s1 =theta1
    s1

% targetJointPosition = [2*pi S0 s1 E0 E1 W0 W1 W2 pi pi -pi/2 pi/4 pi/2 2*pi pi/2 ]';
targetJointPosition = [2*pi S0 s1 E0 E1 W0 W1 W2 S0 s1 -E0 E1 W0 W1 W2 ]';
show(robot,targetJointPosition)
 pause(0.2);
end
for s1 = 0.953:-0.1:0
  s1
% targetJointPosition = [2*pi S0 s1 E0 E1 W0 W1 W2 pi pi -pi/2 pi/4 pi/2 2*pi pi/2 ]';
targetJointPosition = [2*pi S0 s1 E0 E1 W0 W1 W2 S0 s1 -E0 E1 W0 W1 W2 ]';
show(robot,targetJointPosition)
 pause(0.2);
end
```

Figure 9: Cycling Through the All Joint Angles for S1

After achieving this, I then continued to simulate the range of the rest of the joint in a similar fashion and retuned them all back to the initialisation pose before changing joint. A section of the output from this simulation can be seen in figure 10 where the Baxter robot is cycling through the range of angles for S1, where the figure on the left show the initialisation pose and the figure on the right shows the max value of S1.

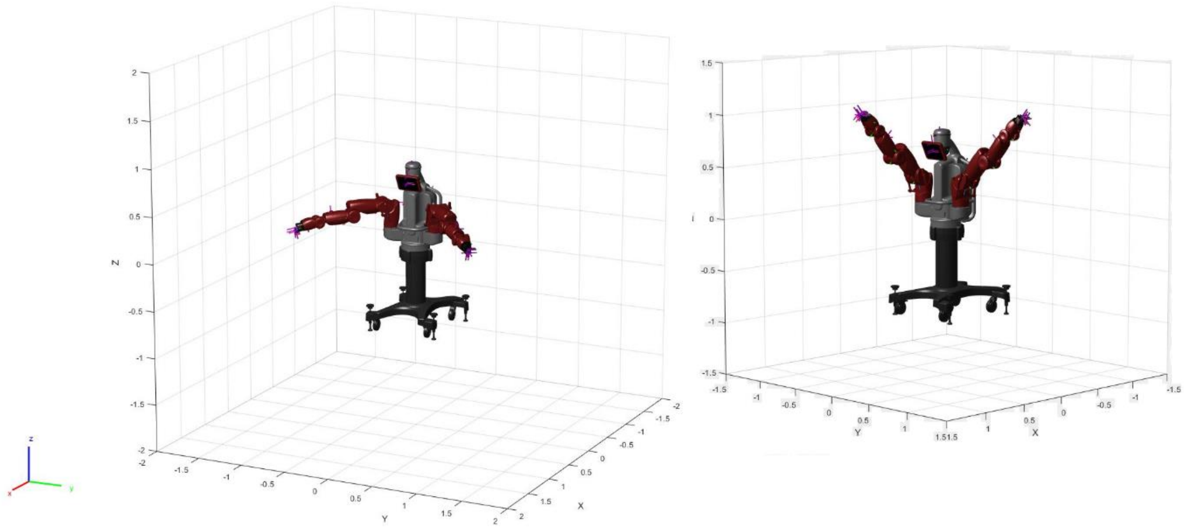

Figure 10: Forward Kinematics 3D Environment

4. Design

4.1 End effector

For this task I've used Autodesk fusion 360 to model a replacement end effector to be attached to the Baxter robot, whilst using Rethink Robotics Electric Gripper Installation manual to acquire the specifications and dimensions (Rethink Robotics, 2015a). In order for the gripper to operate correctly I had to ensure that the design would allow for each of the end effectors to move parallel to one other without colliding. At the same time, it is also essential that whilst achieving this, the gripper also remained aligned in order for the gripper to functionally hold an object within its grasp. The first iteration of the design is shown below in figure 11. The gripper portion of the end effectors have a track which goes down the centre of the outside edge of the model. This allows for a variety of attachments to be fitted to the gripper, one of which being a rubber block which provided a suitable surface material for the gripper to use to interact with objects. The design incorporates two 3mm holes which allows the gripper to be fitted to the Baxter robot using hex screws. And the total length of the grippers base is 80mm which is a mid-size variant according to Appendix 4. Due to how the design of the base has been carried out, it would be very easy to adjust the length of the base to create the additional variations of the gripper to allow for operation of the Baxter robots entire range.

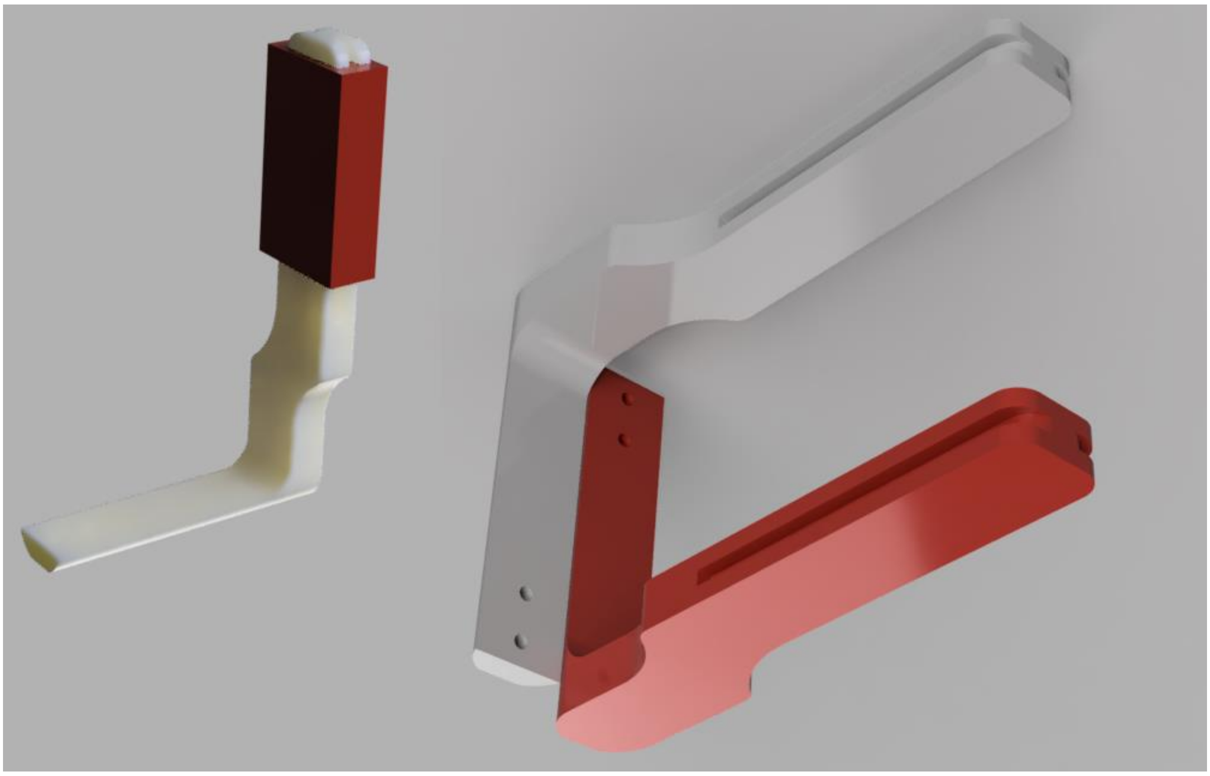

Figure 11: End Effector Initial Design

With the initial design completed I wanted to test the design to see if it was structurally safe when under the full force of the gripper. In order to achieve this, I ran a series of finite element analysis (FEA) tests to determine this. Firstly, I selected the material for the main body of the end effector to be acrylonitrile butadiene styrene (ABS) as it is the closest material to polylactic acid (PLA), which would be my preferred choice. The reason for this is that I wanted the design to be 3D printable using the University's facilities and PLA is the most readily available material. PLA when 3D printed has a Young's Modulus of 3.5GPa, where ABS has a Youngs Modulus of 1.1-2.9GPa when 3D printed (igem, 2015). Due to ABS having a smaller Youngs Modulus the forces that the model can withstand should not cause an issue with using PLA in its place. The material for the rubber attachment was chosen to be silicone rubber. The material properties for the attachment are not significantly relevant to the tests, as they are evaluating the structural integrity of the model, whereas the material for the contact piece is more relevant to surface friction and the end effectors ability to grip and object.

With the material parameters defined, I set the base of the gripper as the constraint and placed a 35N linear load onto the end effector, acting on the rubber attachment; which is the maximum gripping force that the Baxter robot can exert (Rethink Robotics, 2015b). From the FEA results I was able to see factor of safety for the model was at maximum 15, however had a minimum of 2.199, with the max stress, strain and displacement being 9.094Mpa, 0.1321 and 5.972mm respectively figure 12. The data provided by the FEA highlighted that the internal corner of the end effector was causing a weak point within the model and whilst a factor of safety of 2.199 means that the model would be unlikely to break and have a critical failure under the maximum force of the Baxter's grip strength, for safety and unforeseen events such as an external force I would prefer the degree of safety to be at least a factor of five for the entire model (The Engineering ToolBox, 2010). There I decided to make alteration to the design to ensure that it was structurally safe.

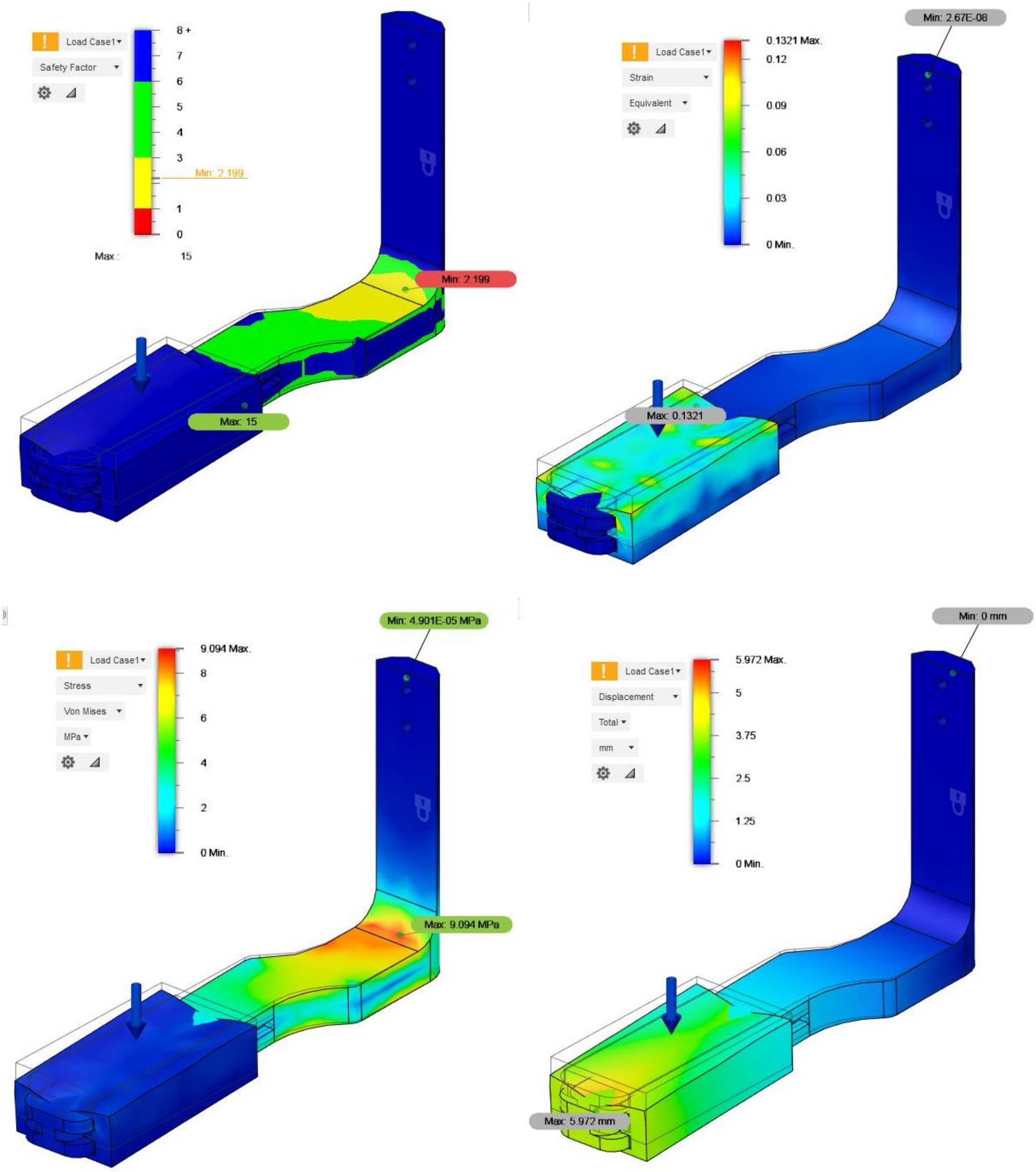

Figure 12: FEA ABS 35N Initial Design

With the weak points of the model identified, I made several changes to the models. Firstly, I increased the size of the fillet in the internal corner of the end effect and added an additional fillet to the external corner of the model. I decided to do this in order to distribute the force acting on the corner over a larger surface area, which will strengthen the weak point within the model, allowing a greater force to be exerted without failure. Secondly, I also increased the thickness of the gripper portion of the end effector by 1.1mm in both directions. The additional material will once again strengthen the weak points by having more material to distribute the force being applied figure 13.

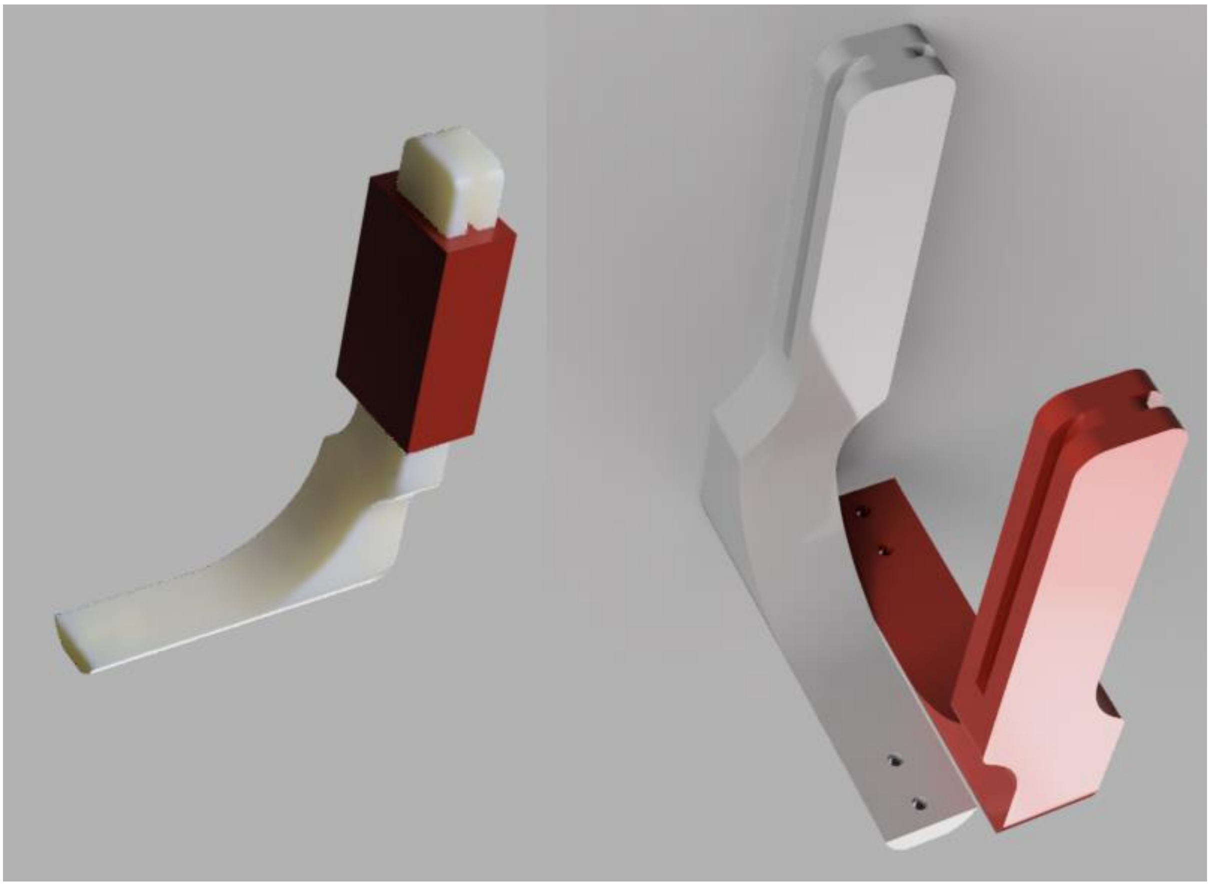

Figure 13: End effector Final Design

With the refined design completed, I then went on to carry out another series of FEA tests. For the tests I used the same constraints, materials, and loads as the previous FEA study. With alterations of the design in place the new minimum factor of safety for the ABS model is now 5.501, which is an improvement from the previous design and meets the standard that I wanted to achieve. The max stress, strain and displacement being 3.636Mpa, 0.01822 and 1.149mm respectively figure 14. Once again from the FEA we can see that the weak point within the model is still the internal corner, however I have been able to successfully strengthen it, to meet the structural requirements set. From the data we can see that the model has improved in all aspects of the FEA, the stress being almost a factor of three times smaller, which concluded that the force has been distributed around the model in a more structurally efficient manner. Whilst the adjustments to the model do mean that the material cost will increase and that the overall model is a more bulky and less streamlined than it previously was, the model is still fully printable which means that the end effector can still be printed and replaced if needed in the future at the University at a low cost.

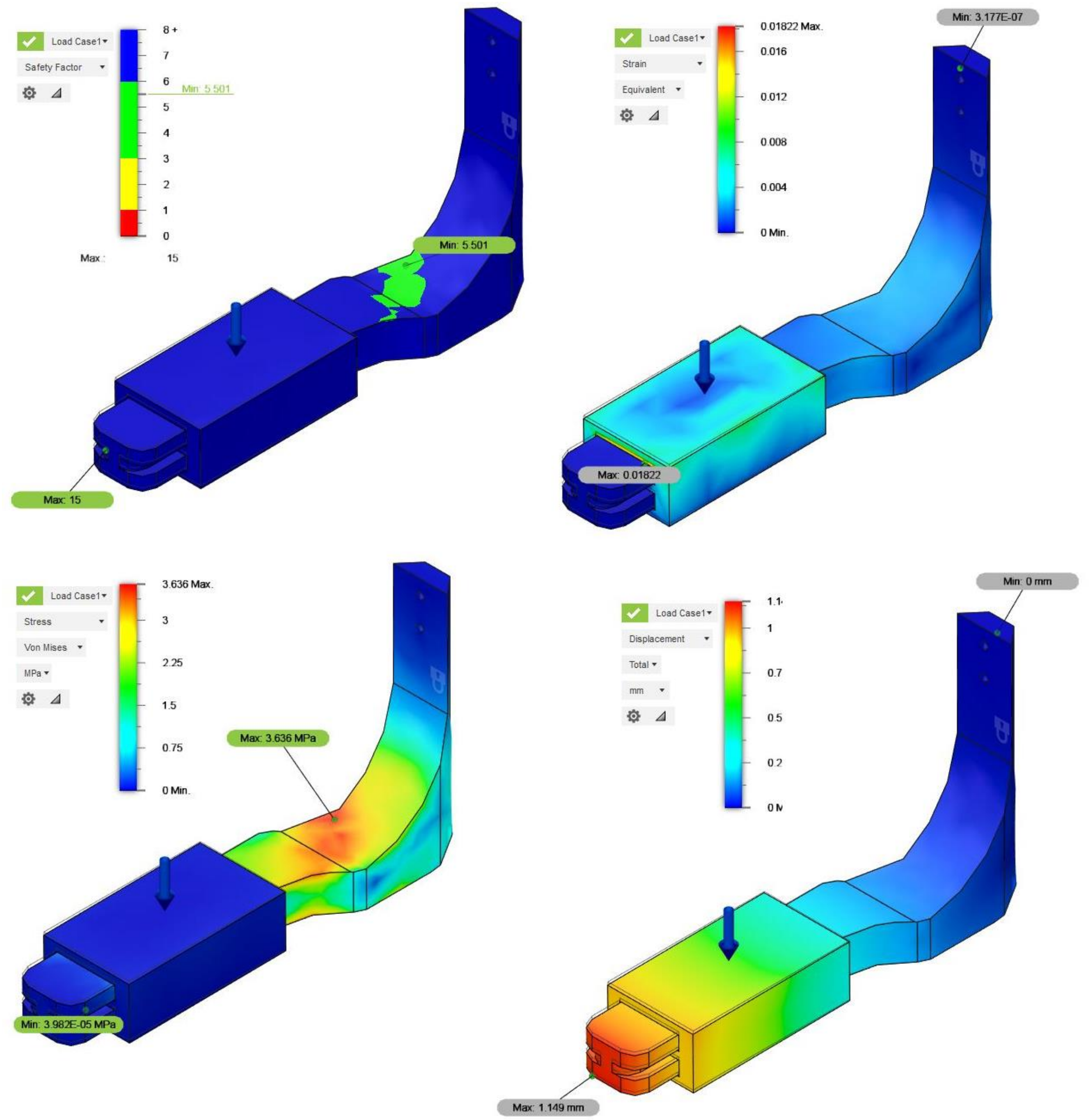

Figure 14: FEA ABS 35N Final Design

As a final experiment I wanted to conduct an additional FEA test, on the initial model to discover if the model would be able to achieve the structural requirements if another material was used in place of ABS. For this test I decided to conduct the study using aluminium, which has a Young's Modulus of 69Gpa (The Engineering ToolBox, 2003), which is larger in comparison to the Young's Modulus of ABS, previously stated as 1.1-2.9Gpa (igem, 2015). With the material selected a new FEA study was conducted using the same constraints and load of 35N and the results concluded that the new minimum factor of safety is now 15, which is around three times higher than the factor of safety when using ABS as the material. The results also state that the max stress, strain and displacement being 9.79Mpa, 0.01401 and 0.1766mm respectively figure 15. Whilst the results do provide confidence in the initial designs ability to meet the structural requirements to withstand the maximum force of Baxter gripper (35N), with a factor of safety being above five, the manufacturing process is now more complex. With the use of materials such as ABS and PLA the model would be able to be manufactured at the University by method of 3D printing. With this method of manufacture, a new print of the model would be very easy to achieve and very cheap. Due to the method of 3D printing there is very little waste product; with most of the waste being structural supports to aid the printing process. However, in order for the aluminium gripper to be manufactured, the model would have to be machined from a larger piece of aluminium, which produces a high volume of waste product and thus drives the cost up for the model to be produced. Overall, both designs show promise and have confidence in their abilities to withstand the required forces, dependent on their material of manufacture. Part of my goal for the design of the replacement end effector for the Baxter robot is that, if required a new replacement could be readily produced in the future, therefore I believe that the best material to base the design around is PLA and ABS, as it would make the manufacturing inexpensive. The main advantage of the aluminium model is that it provides a higher level of protection for the end effector against external forces which could be greater than 35N, however a key point to consider is that it is preferred that the easily replaced gripper is broken when exerted under extreme forces, than for the gripper to survive but for Baxter to break in its place.

Model	Material	Minimum Factor of Safety	Max Stress (Mpa)	Strain	Displacement (mm)
Initial (ALU Model)	ABS	2.199	9.094	0.1321	5.972
Initial (ALU Model)	Aluminium	15	9.79	0.01401	0.1766
Final (ABS Model)	ABS	5.501	3.636	0.01822	1.149

Table 2: Data from FEA Testing

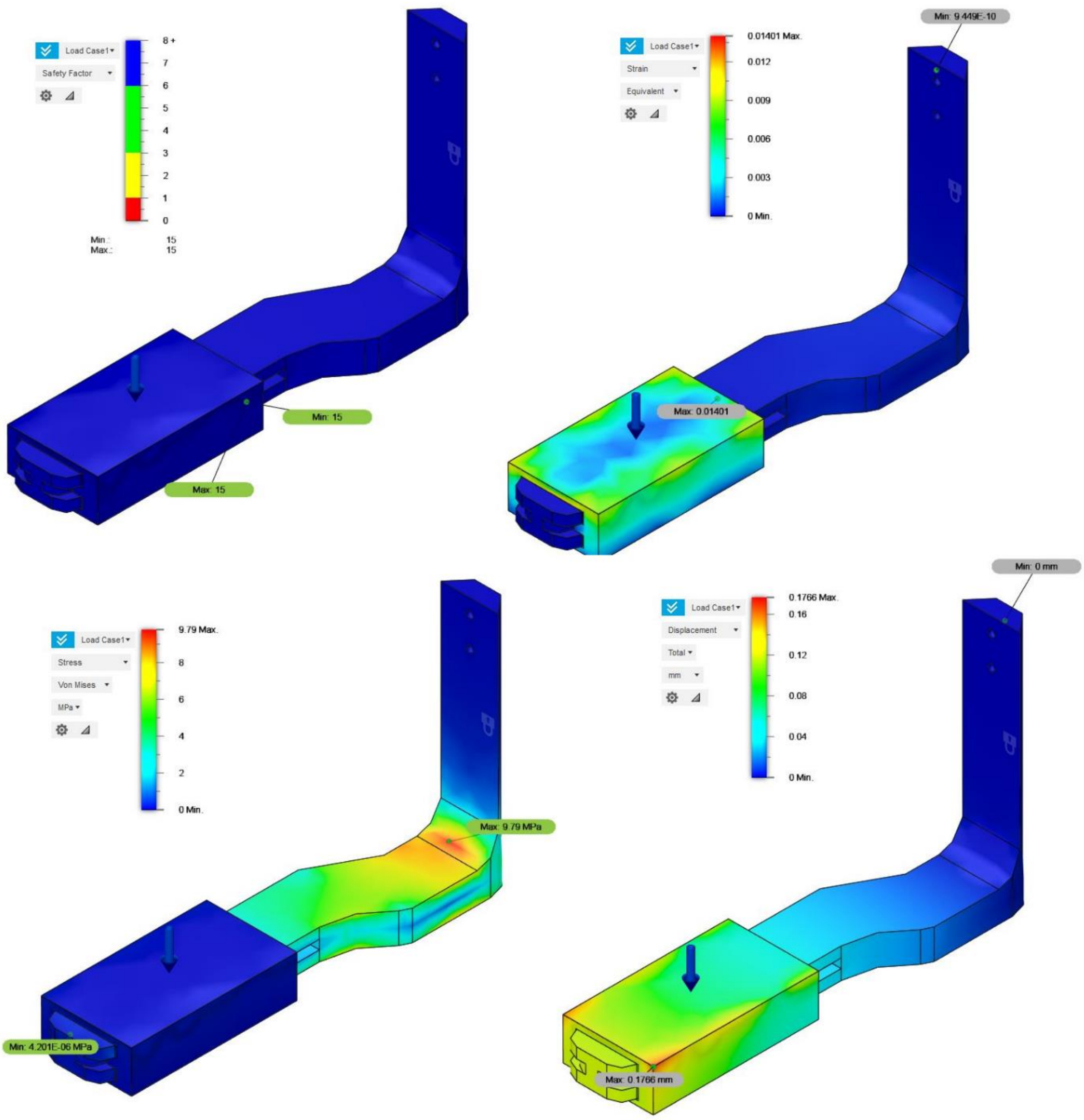

Figure 15: FEA ALU 35N initial design alternative material

4.2 ROS Gazebo 7 Simulation of Baxter

Alongside physical repairs one of my goals was to provide a digital workstation and coding framework, which would allow future research to be carried out using the Baxter robot at the University of Plymouth. I chose to base the workspace around using ROS (Robot Operating System), as ROS is a standard framework within the field of robotics for writing and sharing software (ROS, 2020). In addition, Rethink Robotics also provided a toolbox to control and operate the Baxter robot, upon its initial release. Rethink Robotics provides a manual to set up the workstation to control the Baxter robot (Rethink Robotics, 2015c), with software that was released in 2012 and last updated in 2015. The current software and documentation are using legacy versions of both Ubuntu 14.04 and ROS Inigo, which means that this software (without changes) is not compatible with the University's software setup, which uses Ubuntu 16.04 and ROS Kinetic.

Due to the University's laboratories being shut because of COVID-19, my research was carried out at home using a VMware Workstation running a 64-bit boot of Ubuntu 16.04 with the specifications shown in figure 16.

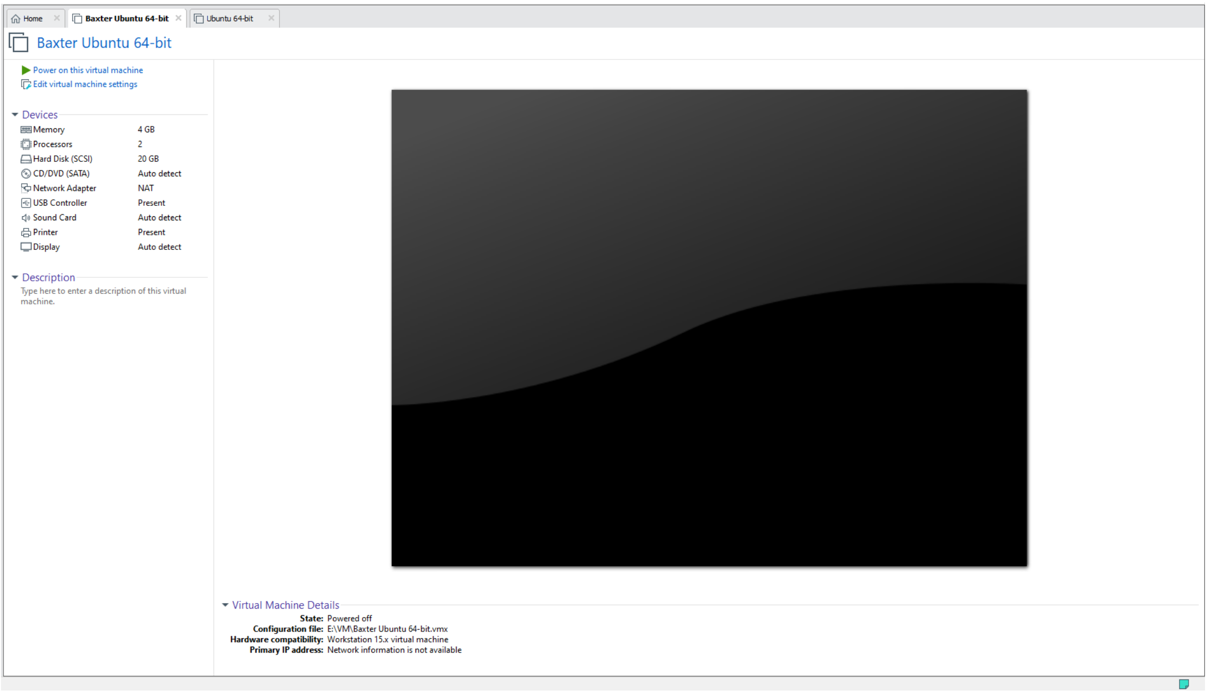

Figure 16: VMware Workstation setup for 64-bit Ubuntu 16.04

With a standard install of ROS Kinetic installed and a workspace created, the code in figure 17 downloads Rethink Robotics' SDK for the Baxter robot from their GitHub repository.

```
## Install the SDK for Baxter
$ cd ~/ros_ws/src
$ wstool init .
$ wstool merge https://raw.githubusercontent.com/RethinkRobotics/baxter/master/baxter_sdk.rosinstall
$ wstool update
$ source /opt/ros/kinectic/setup.bash
```

Figure 17: Code to install Baxter SDK

Once the SDK has been downloaded, we need to next compile the workspace, which is achieved by using the catkin_make command in the terminal figure 18.

```
$ cd ~/ros_ws
$ catkin_make
$ catkin_make install
```

Figure 18: Compiling the workspace

After the workspace has compiled, we next need to configure the baxter.sh file with the parameters of the current workstation figure 19.

```
##Configure Baxter Coms with the workspace
$ wget https://github.com/RethinkRobotics/baxter/raw/master/baxter.sh
$ chmod u+x baxter.sh

$ cd ~/ros_ws
$ gedit baxter.sh

```

Figure 19: baxter.sh

In the baxter.sh file, in order for the workstation to be used within a simulation the baxter_hostname has to set to “my_computer.local”, however if the user wants to interact with the physical Baxter robot rather than the simulation, the variable “your_ip” needs to be set to the workstations ip address. Additionally, the variable of ros_version, needs to be set to “kinetic” in order for the software to work with the correct version of ROS figure 20.

```
#-----------------------------------------------------------------------------#
#                 USER CONFIGURABLE ROS ENVIRONMENT VARIABLES                 #
#-----------------------------------------------------------------------------#
# Note: If ROS_MASTER_URI, ROS_IP, or ROS_HOSTNAME environment variables were
# previously set (typically in your .bashrc or .bash_profile), those settings
# will be overwritten by any variables set here.

# Specify Baxter's hostname
baxter_hostname="baxter_hostname.local"

# Set *Either* your computers ip address or hostname. Please note if using
# your_hostname that this must be resolvable to Baxter.
your_ip="192.168.XXX.XXX"
#your_hostname="my_computer.local"

# Specify ROS distribution (e.g. indigo, hydro, etc.)
ros_version="kinetic"
#-----------------------------------------------------------------------------#
```

Figure 20: Configuration of ROS Environment Variables

With the workstation now setup, Rethink Robotics’ Baxter simulator can now be installed. Rethink Robotic provide a manual which is compatible with ROS kinetic and therefore no changes need to be made from the original documentation (Rethink Robotics, 2015d). The Baxter simulator uses gazebo 7 as its simulation environment and in order to run the software the accelerate 3D graphics option needs to be unticked on the virtual machine settings figure 21.

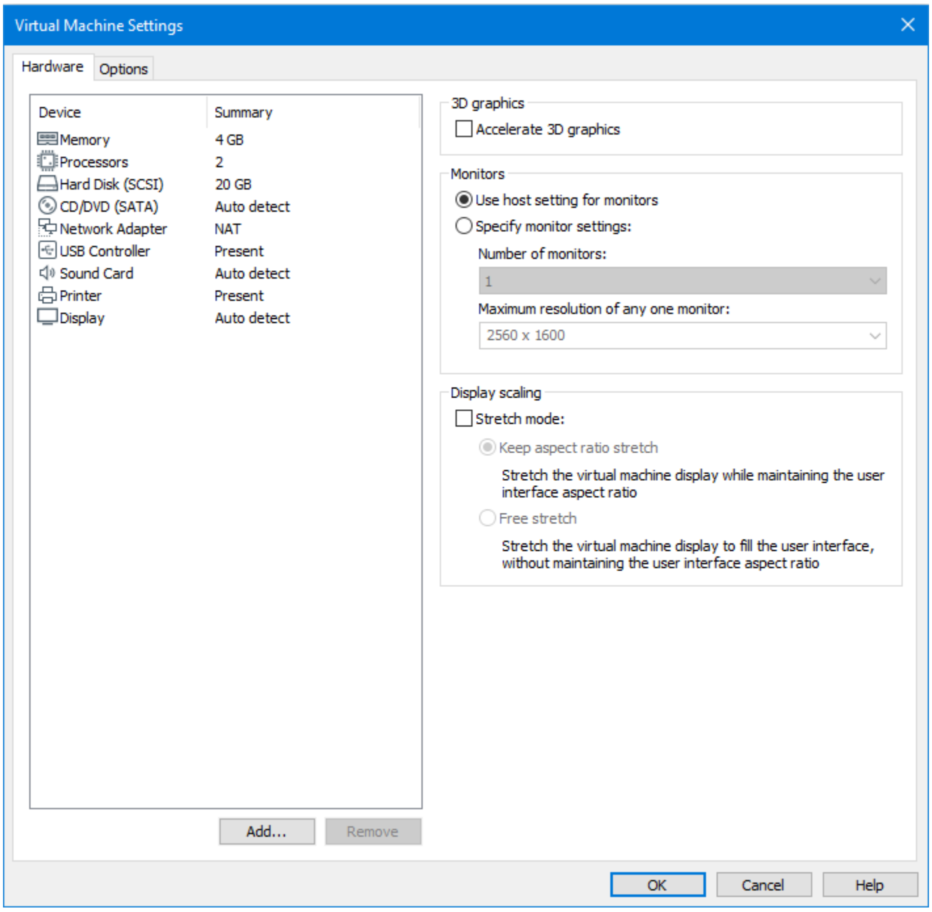

Figure 21: Virtual Machine Settings for Gazebo 7

As a default the simulator comes with a repository of a few prewritten test programs that Rethink Robotics have provided which allow the user to test and interact with Baxter within the simulation. One of the programmes, joint_position_keyboard.py allows for the user to control each one of the Baxter robots' servos (including the gripper) by entering keyboard inputs into the command terminal. This then increments or decrements the value of a joints position by a fixed amount and is shown on the full model of Baxter within the Gazebo 7 environment figure 22. With the framework of this programme a study could be conducted to have the user interact with the Baxter robot to run a simple pick and place exercise. Another programme that was used was a joint velocity wobbler programme in combination with the joint position controller, which had the Baxter robot, move its servos in random direction, whilst the measuring the steady state errors, with the steady state error being the difference between the input signal to the system and the resultant output of the system. This allows the user to test the robot in order to tune the feedback controllers that's being used with the simulation by adjusting its values, to achieve more accurate results when positioning the arms (figure 22). This could be further experimented with by adding a random value as an input to observe how the PID controller would handle an error. With these observations made, the PID controller could be tuned to be able to respond effectively to the steady state error of the arms movements. Whilst the steady state error can be simulated, experiments using the real Baxter robot would still be required to calibrate the PID controller as the error caused by each servo will differ from the random input style error generated to test in simulation.

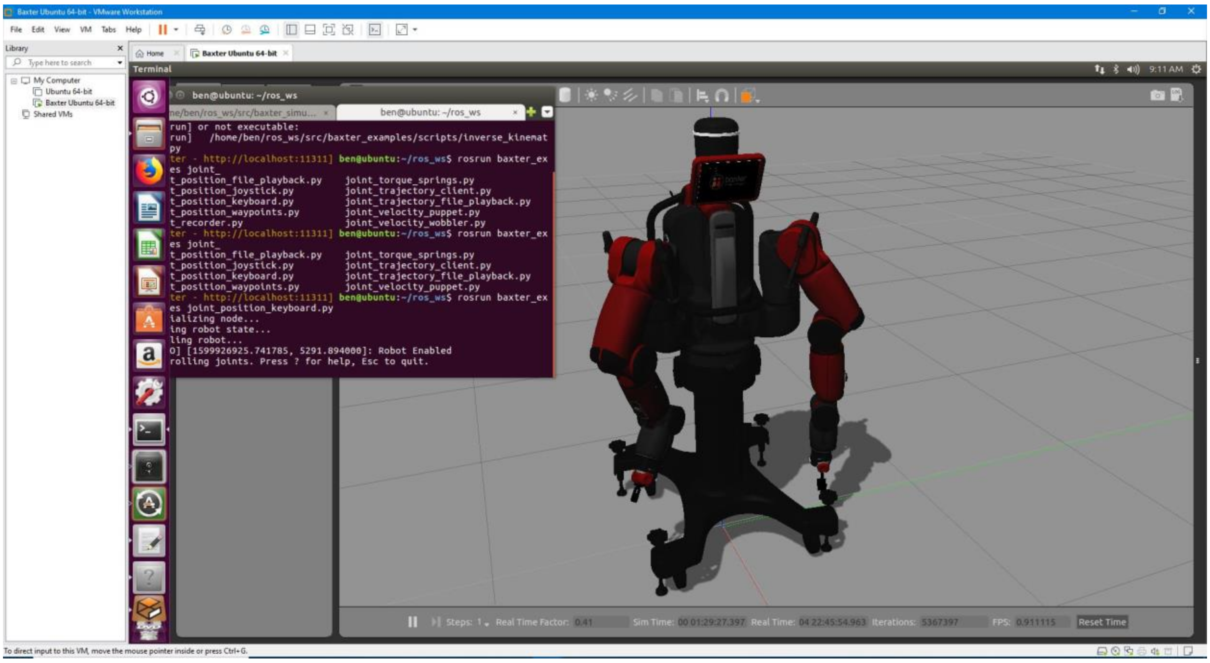

Figure 22: Gazebo Simulation using joint_position_keyboard.py

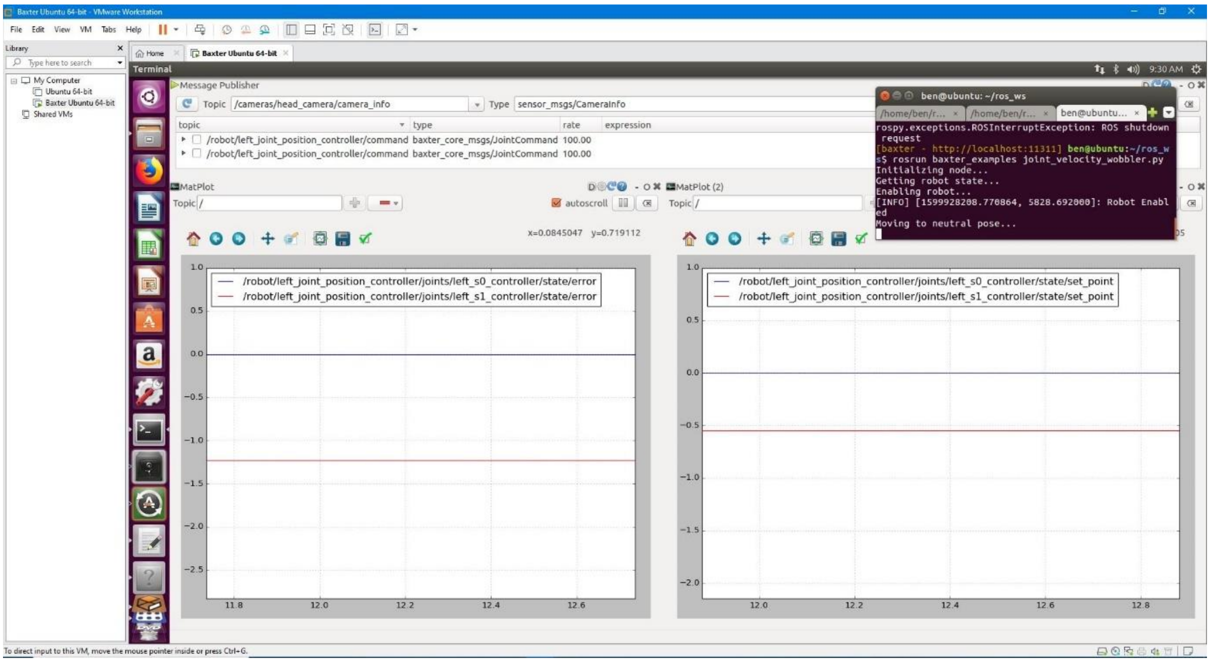

Figure 23: Joint_velocity_wobbler with joint_position_controller

4.3 Semaphore Signalling

After establishing that the Gazebo simulation was set up and operating correctly, I started to create my own piece of software that would allow a user to operate with the Baxter robot. The concept of the programme was to implement a similar style of interaction seen in the joint_position_keyboard.py test programme, however this time when the user enters a letter using keyboard inputs it would set Baxter's joint angles of his servos in his arms a pose that would represent the letter as a semaphore signal. Semaphore signalling is a system designed by the Chappe brothers in the 18th century (Centre of Innovation in Mathematics Teaching, 2006) and is a method of using two flags to signal letters by the position of the user's arms when holding the flags. However due to performance issues and complications with the Gazebo simulation I decided to carry out the simulation using MATLAB instead, which was partially because I was able to integrate the programme with the rest of the project and also because the MATLAB simulation was more stable that the Gazebo simulation. Despite the change in software, the principle and application of the concept remains the same.

The MATLAB programme follows the same principle, the user has the option to enter the characters of Baxter's name into the command window of MATLAB. If a correct key is pressed, Baxter positions his arms to represent the corresponding semaphore signal. This is achieved with the use of the forward kinematics, established earlier in the project. A demonstration of this can be seen in figures 24-29.

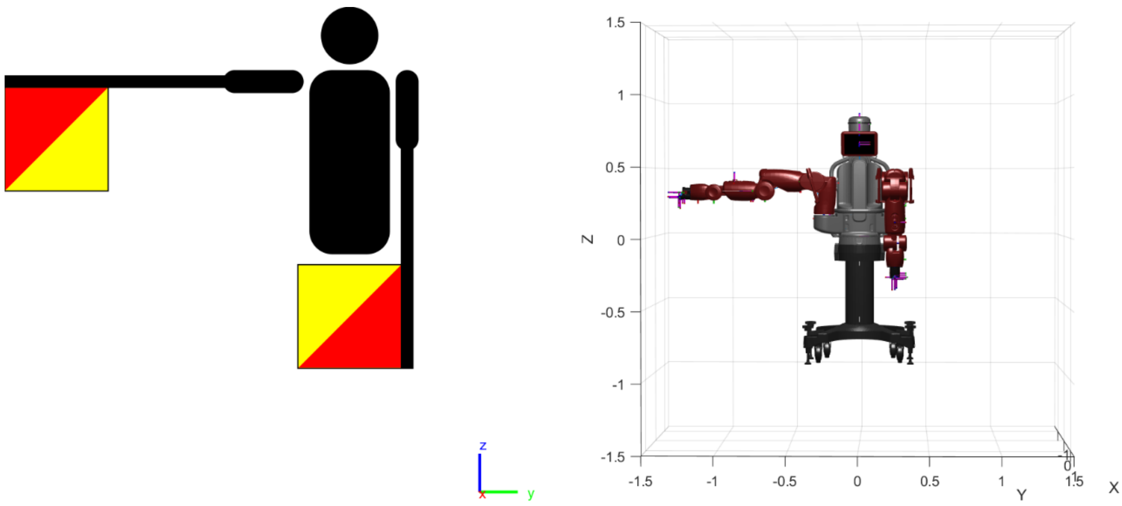

Figure 24: Semaphore signal for B

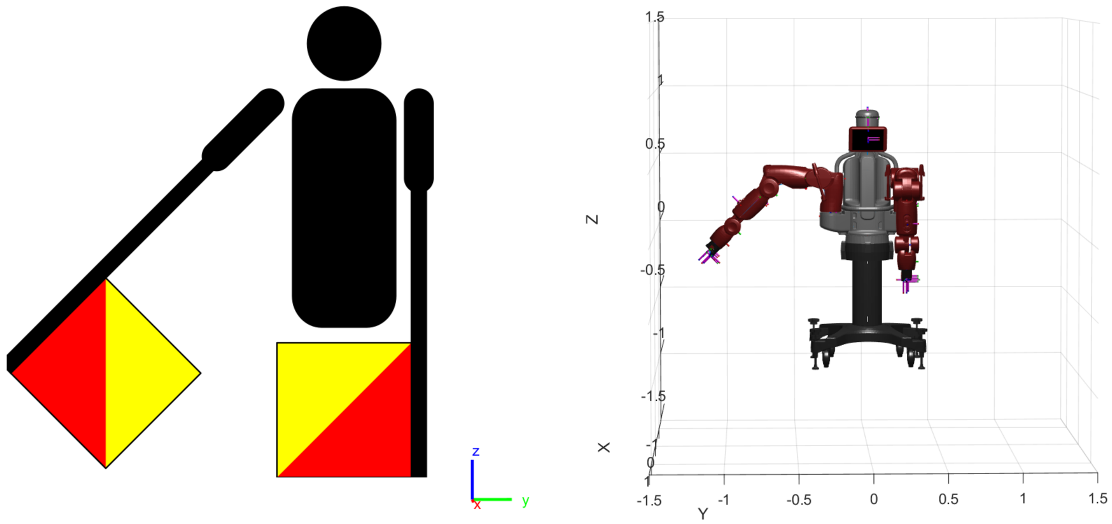

Figure 25: Semaphore signal for A

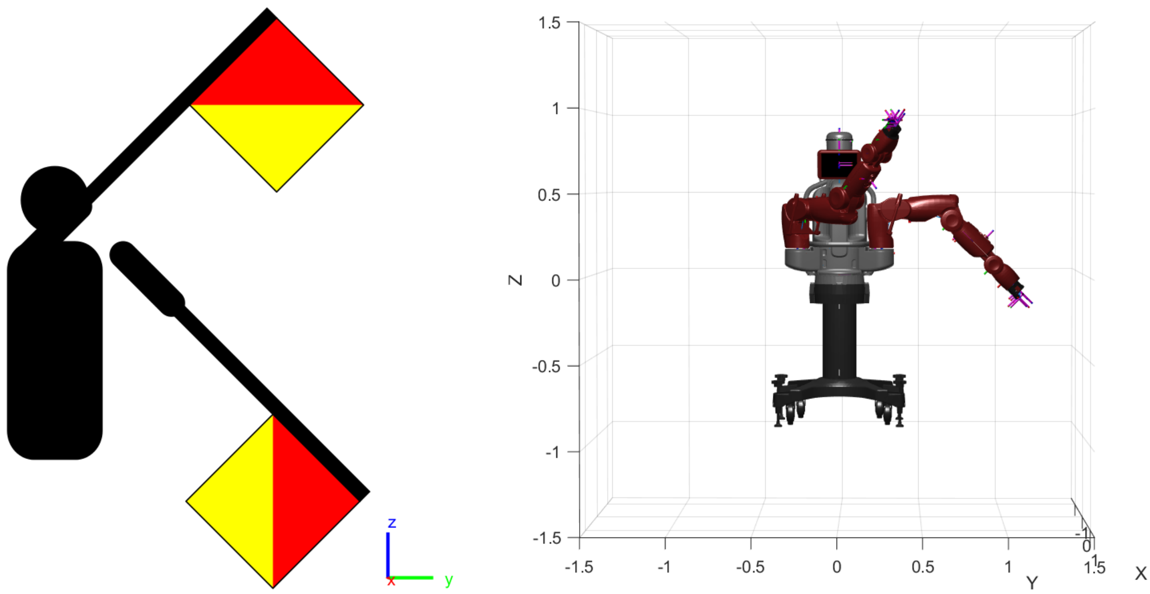

Figure 26: Semaphore Signal for X

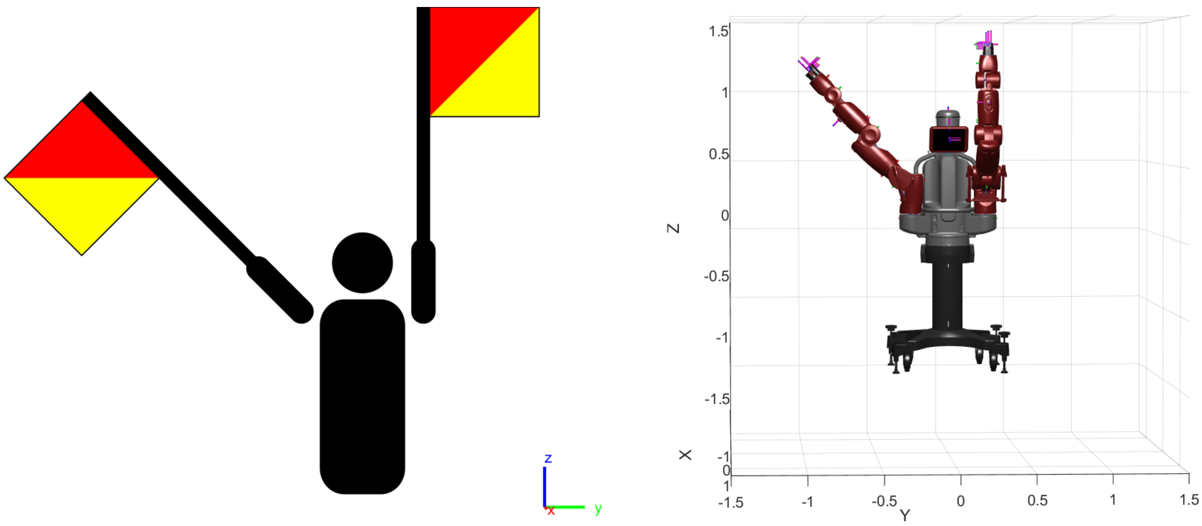

Figure 27: Semaphore Signal for T

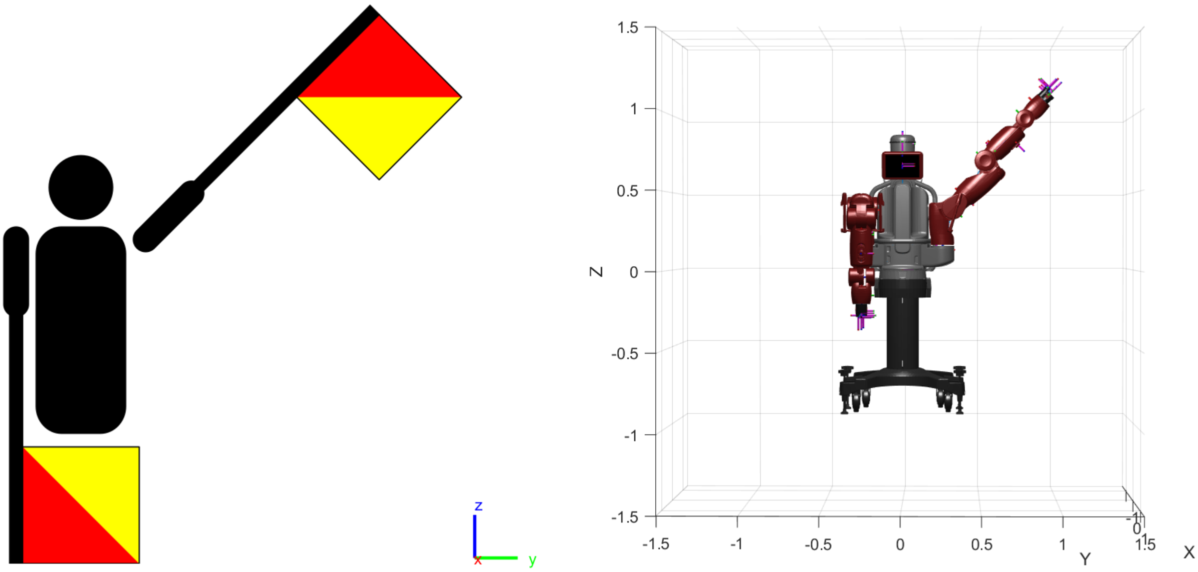

Figure 28: Semaphore signal for E

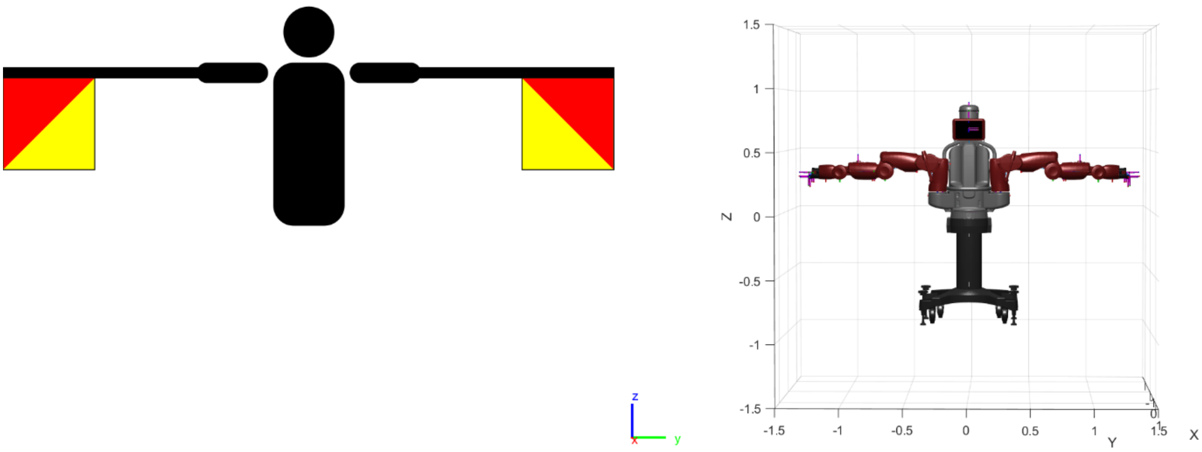

Figure 29: Semaphore Signal for R

5. Discussion and Analysis

5.1 CAD

The design for the replacement end effector offered two different varieties depending on the material selected, with the options being 3D printable PLA/ABS or machined aluminium. Both of the designs are relatively similar, with the main difference being that the PLA/ABS design has more material on the base of the gripper that would be attached to Baxter and a longer fillet on the bend. The reasoning behind these additions to the original design (aluminium variation), is to provide a better distribution of force along the bend. Without the additional material the minimum factor of safety with a force of 35N applied, was only 2.199, whereas with the changes it was 5.501, which is achieved the standard that I wanted to achieve in order to provide a piece of equipment that was structurally stable to be used rigorously without concern of breaking. Additionally, the minimum factor of safety for the aluminium design with the same constraints and forces applied was 15, which more than exceeds target factor of safety of 5.

In addition to the added cost of machining a piece from aluminium in comparison to 3D printing one, another drawback could be the aluminium designs hight factor of safety, which means that the end effector could theoretically suffer an external impact force of up to 525N before catastrophic failure of the part. Whilst providing a structurally strong and stable part of a certain quality is important so then the grippers of the end effector will not require constant replacement, it is also important to consider the forces that would be applied to the rest of the robot if the end effector experiences a large impact force. With the Baxter robot's servos costing more than a replacement gripper it is perhaps best to design the gripper to break at a predetermined threshold, which would allows for the gripper to be used within normal operation without issue, but would break when experiencing extreme force, in order to protect the servos and their gear boxes. With that in mind the PLA/ABS design may be the better design, but both designs have their benefits and drawbacks.

Whilst the PLA/ABS design is cheaper to produce it may not be the best material choice for some situations. For example if you wanted to use the Baxter robot to carry out research into cooking robots, the high temperature of objects within that environment that Baxter would be interacting with may cause the end effector to take damage due to the heat melting part of it, with the print bed temperature being around 72^{0}C for PLA (igem, 2015). Due to the environmental elements surrounding this particular task, the end effector using the aluminium grippers would be better suited over the 3D printed PLA/ABS alternative.

With the two iterations of the grippers both achieving all of the design requirements to ensure the end effector will be functional, they both require physical testing with the actual Baxter robot, before I can say for certain that the design is finalised and without any major faults or oversights. Due to the COVID-19 Pandemic, I was not able to gain access to the Baxter robot at the University of Plymouth throughout the process of the project which meant that the parameters that the for the gripper were obtained from partially from data sheets and other reference images and materials, therefore a few parameters may need to be fine-tuned once access to the Baxter robot to obtained. The main concern is the alignment of the base, whilst the grippers have been designed to work smoothly in a pair to provide a vice like gripper action, the screw holes may need to be adjusted, which could cause the need for an modification to the base to be made.

5.2 Kinematics

The kinematics derived and demonstrated within this project show examples of both forward and inverse kinematics. For the purposes and scope of the project the kinematics are purely theoretical and demonstrated in a perfect system, and therefore don't fully represent a real system. In a real system, such as using the kinematic model with the physical Baxter robot, the servos would not be perfect and therefore the location of the end effector within a 3D plane may experience some compound drift. Due to experiencing drift the certainty of the position of the end effector would decrease, however a solution to this could be solved by the use of a closed loop feedback control system. The implementation of a closed loop feedback control system can be used to increase the accuracy of the end effector by providing feedback data which will allow for adjustments to be made to the joint angles of the servos to reach the required goal. Several methods could be used as a solution this issue including a simple proportional-integral-derivative controller (PID controller) or a Kalman filter.

With the forward kinematics the model of Baxter within MATLAB could be successfully implemented to calculate the pose of the Baxter robot using the joint angles as a control input. The method of forward kinematics is well suited for manual control of the Baxter robot, which would be ideal for situations where the user would be controlling the robot via teleoperation. Whilst in the MATLAB programme the joint angles need to be inputted using a keyboard, control of the joint angles could be provided by the use of a controller that would allow the user to increase and decrease the value of the joint angles, whilst providing an easy way for the user to switch between the selected joint to interact with. With a human operator controlling the robot, there is less requirement for a closed loop feedback controller, as the operator is acting as such system.

Similar to the forward kinematics, the inverse kinematics were also successfully demonstrated using a model of Baxter with MALAB, with the user imputing the target coordinates. Inverse kinematics are useful when integrated with an autonomous system, as they allow for the user to input the target location of the end effector and for the robot to provide a solution for the joint angles. However as discussed, over or undershoot may provide an issue when using an open loop system with forward kinematics, which is why a closed loop feedback system preferred to maintain accuracy.

5.3 Interaction

The interaction element of the project was originally focused around using the Gazebo simulation of the Baxter robot in ROS, with the idea of having Baxter carrying out semaphore signalling. However, the semaphore signalling interactive programme was instead carried out in MATLAB using the forward kinematic model that I had implemented earlier in the project. Whilst in the programme Baxter can carry out the required gestures to spell out his own name using semaphore signals, he does not currently use signalling flags to properly convey the message. With access to Baxter, further research could be carried out with Baxter interacting with a set of signalling flags, where a project could be centred around using Baxter as a translator from variable or written commands to semaphore signalling. It is also possible that with the use of computer vision that Baxter could be taught to read semaphore signals, to then be used as input commands. In order to do this Baxter would need to make use of RGB-D camera to track the skeletal data of a user which could then be used with a machine learning programme to match the data with predetermined poses (Win, S. et al., 2020).

In addition to the semaphore signalling programme, experiments were also carried out using the Gazebo 7 ROS simulations using Baxter to test some of the programmes provided by Rethink Robotics. This included being able interact with Baxter with the use of keyboard inputs that would change his joint angles and the joint velocity wobbler programme in combination with the joint position controller. Whilst the experiments provided detailed visuals of the Baxter robot operating, the simulation experienced a large amount of lag, which is believed to be caused by the virtual machine not having the required resources to run a resource heavy simulation. To confirm this further testing will be required in the University's labs, where the computers are better suited to carry out such a task. Alternatively, the software is quite old and a new alternative simulation environment, such as v-rep may be beneficial.

5.4 Literature and Teaching

From the literature review it became clear that Baxter still has a lot to contribute towards research, especially within the field of robot-human interaction. Whilst the literature covered was broad in scope, it highlighted the fact that Baxter has a lot of potential outside of the usual tasks and operation usually associated with the robot, which are usually industrial based. With the Baxter robot having a lot of potential research opportunities into different field, it's creates a valuable platform to use to teach a variety of different practices within robotics. Besides having the ability to aid the teaching of kinematics and forces, Baxter provides an opportunity to learn about human-robot interaction alongside the interaction of tools, equipment and objects. Due to the nature of the subject this would then require knowledge and application of computer vision systems, machine learning, control theory, neural networks, alongside the understanding of coding in software such as MATLAB and ROS. Therefore, because of the versatility of the Baxter robot, he can be valuable resource for research and teaching purposes.

6. Future work

Beyond this project I would like to further explore different areas of research using the Baxter robot. With the laboratory open again I would like to carry out physical testing on the real Baxter robot using both the grippers and kinematic models. I would also like carry out experiments to test the accuracy of the Baxter robot. To do this I would use the robotic toolbox in MATLAB to generate a trajectory for Baxter to follow, which could be applied to both simulation and physical robot. With these tests I can record the position data for the arms in their end positions, which can be used to evaluate the accuracy by making a direct comparison between the two results.

Additionally, to calibration tests I would also like to carry out a series of projects using the real Baxter robot. Firstly, I would like to continue to work with the Baxter robot to further the semaphore signalling system that has been developed within the project. In a future study I would like to train the Baxter robot to recognise a semaphore signal and to be able to repeat the signal. This would be achieved with the use of a depth camera which could be used to carry out skeletal tracking of a human producing the signals. With the skeletal data recorded, the data could be converted to forward kinematics for Baxter to replicate to reproduce the same signal. Baxter could also use the values of the joint angles to determine the identification of the semaphore signal, which would allow for him to translate the signal. A similar experiment was carried out using the pepper robot by Tian, N. et al., (2018), where they used cloud computing to mirror semaphore signals.

Another project that I would also like to pursue would be the use of Baxter as a cooking robot, that could be used within an industrial or home environment. For a robot to be capable to perform a cooking task autonomously, computer vision will be a key tool to achieve its goal. In a study carried out by Ikegami, N. et al., (2020) they investigated methods of cutting objects within the kitchen environment. In order to achieve this goal, they implemented an EMD Neural Network to train the robot to carry out a cutting action depending on the desired result. The robot used an Xbox Kinect camera to provide 3D image data of the environment that the robot would be operating in, this sort of set up can be seen in multiple different studies using the Baxter robot include one carried out by Avalos, J. et al., (2017). Whilst the research was carried out only in simulation, the results show promise that this method could be applied to a real-world robot, given similar shaped objects to cut. Additionally, in a study carried out by Zhu, Q. el al., (2017), the ARMAR-III kitchen robot created by the Karlsruhe Institute of Technology (Robots IEEE, 2020e) was used to carry out research which was mainly focused on a verbalisation system for the robot to recognise what task it was carrying out and to convey a concise report. The activities that the robot would complete would include mixing, pouring, wiping, along with kitchen-based pick and place interaction, which was achieved due the use of the robot's stereo vision. Once again with an Xbox Kinect camera fitted to Baxter, research into cooking and kitchen application for Baxter are achievable. Lastly in a study carried out by Junge, K. et al., (2020) and RGB-D camera was used alongside a Bayesian filter in part of a feedback system which would allow a robot to cook a perfect omelette by using the RGB data to achieve the desired result.

Due to Baxter's compliant joints and with the use of torque sensors, which allow him to work safely with humans, Baxter would be an interesting robot to carry out cooking related tasks. Whilst with machine learning and neural network application, Baxter could be programmed to complete kitchen tasks autonomously, Baxter could also be controlled via teleoperation to allow a user to carry out kitchen an external environment. This could be used in combination with a VR headset, which can be seen achieved in a study by Lipton J.I. et al., (2018) which would allow the user to see the environment from Baxter's perspective. The user could then make suggestive movements using VR controllers in combination with Baxter's torque force sensing to ensure that the appropriate force is being used to carry out a task such as cutting vegetables or gripping a saucepan.

7. Conclusion

Overall, to conclude the project has successfully achieved all four of the objectives that were established at the beginning of the project. The project has provided two separate designs for grippers to be used to repair the end effects on the current Baxter robot at the University of Plymouth and a working model and interactive programme has been created in MATLAB. Which includes forward and inverse kinematics, along with semaphore signalling. Following the literature review into the Baxter robot in relation to several fields within the industrial and domestic use, it was concluded that Baxter has a lot of potential to be used for research into areas which involve robots and human interacting within the same environment. It was also established that due to Baxter's multidisciplinary potential, he also provides a valuable platform to teach students about numerous applications and principles of robotics. Due to not being able to obtain access to the Baxter robot within the University's laboratories, instead of carrying out physical testing with Baxter, an investigation into potential future projects was carried out, with both looking at the further applications of semaphore signalling and cooking application of the Baxter robot. With the conclusion of the project, the first steps towards Baxter's restoration have been completed, with a toolbox provided as a starting point for future research to be carried out.

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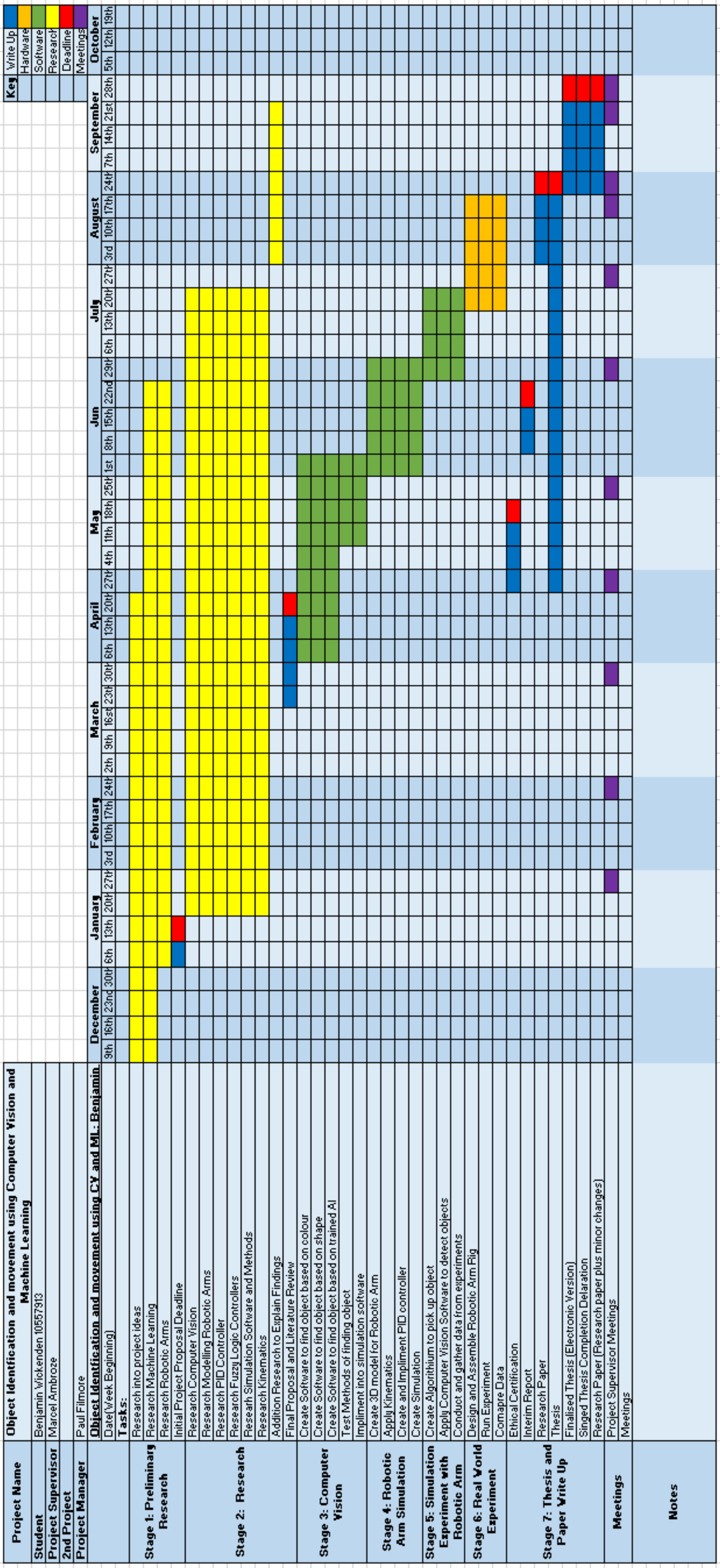
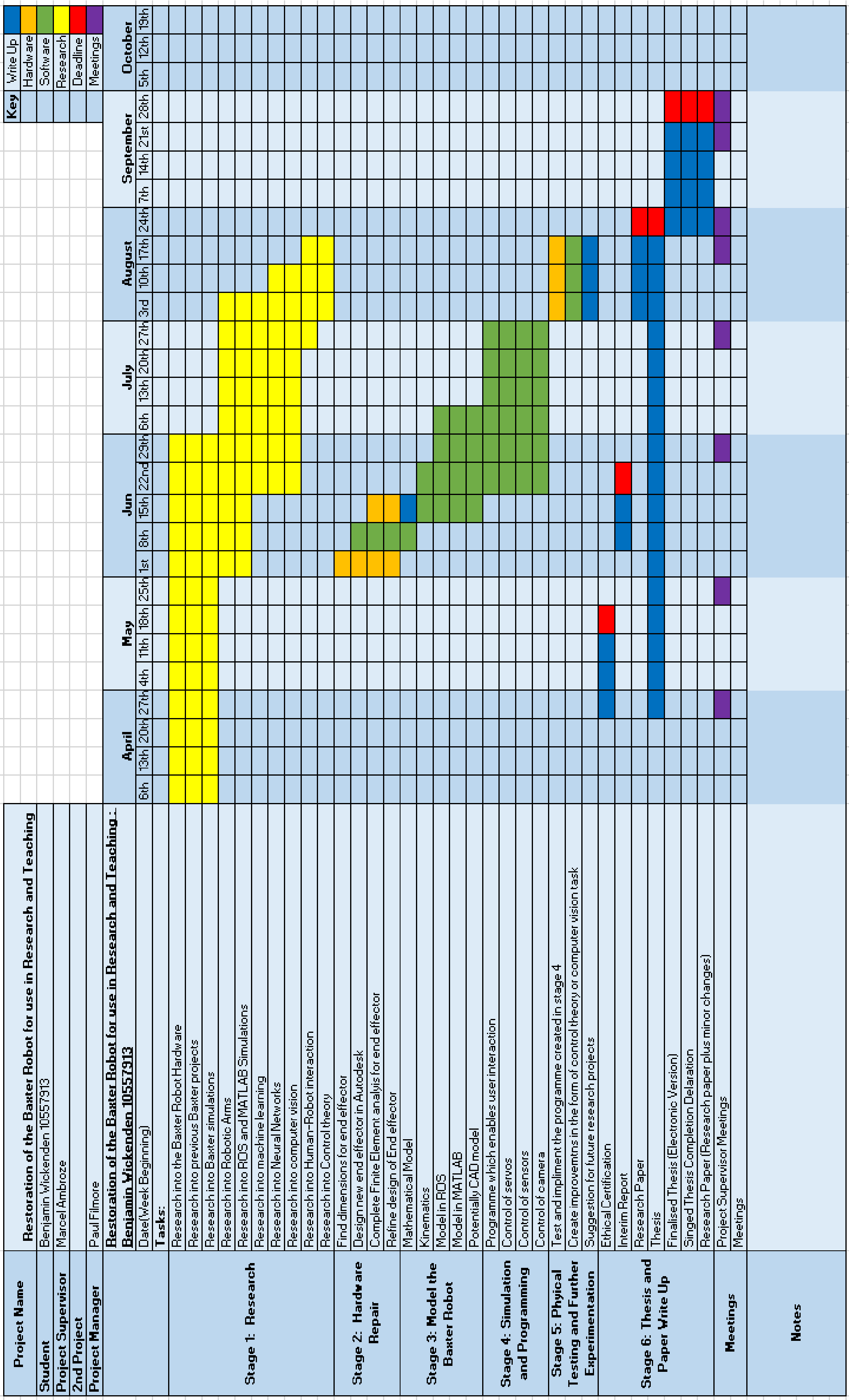
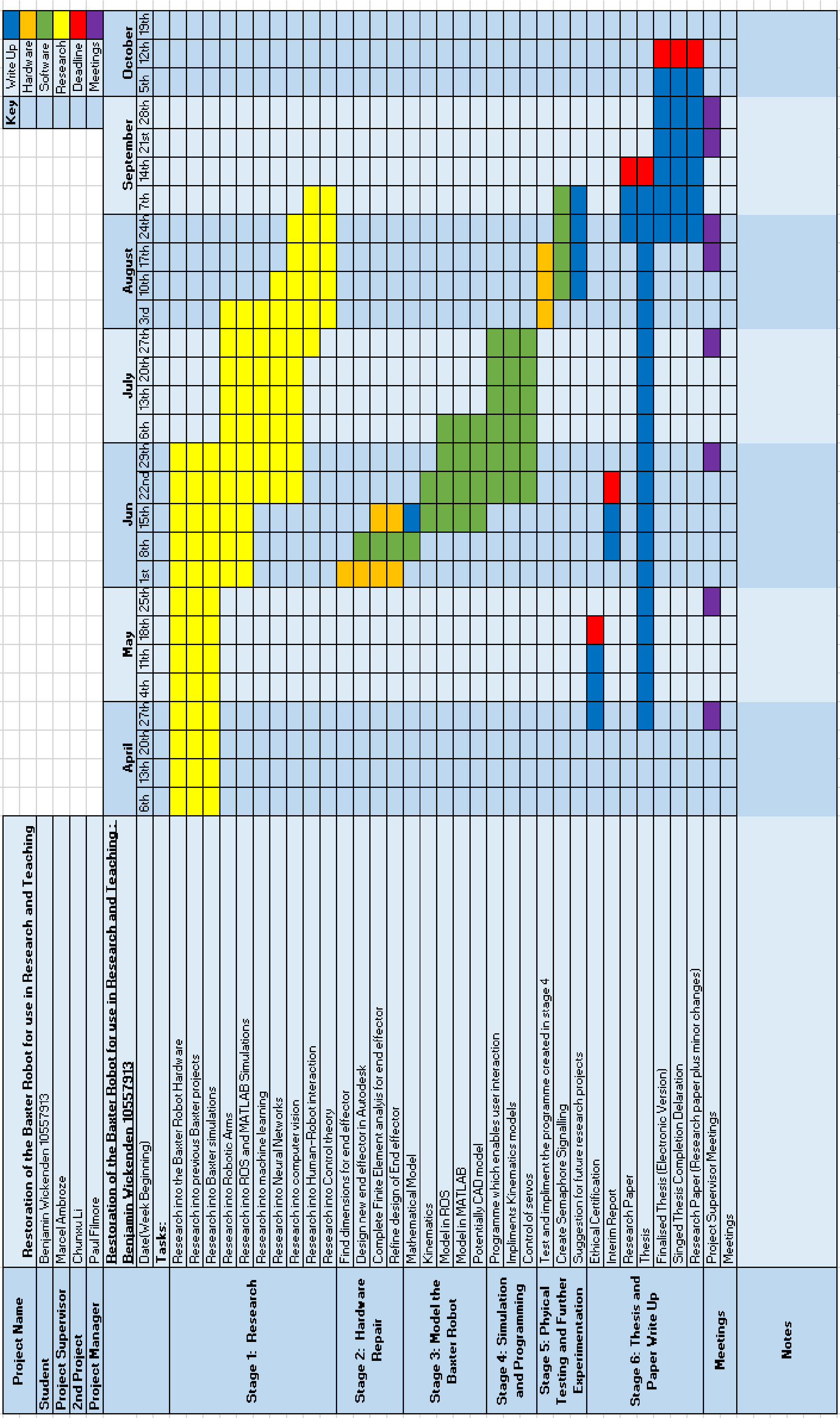
9. Appendix



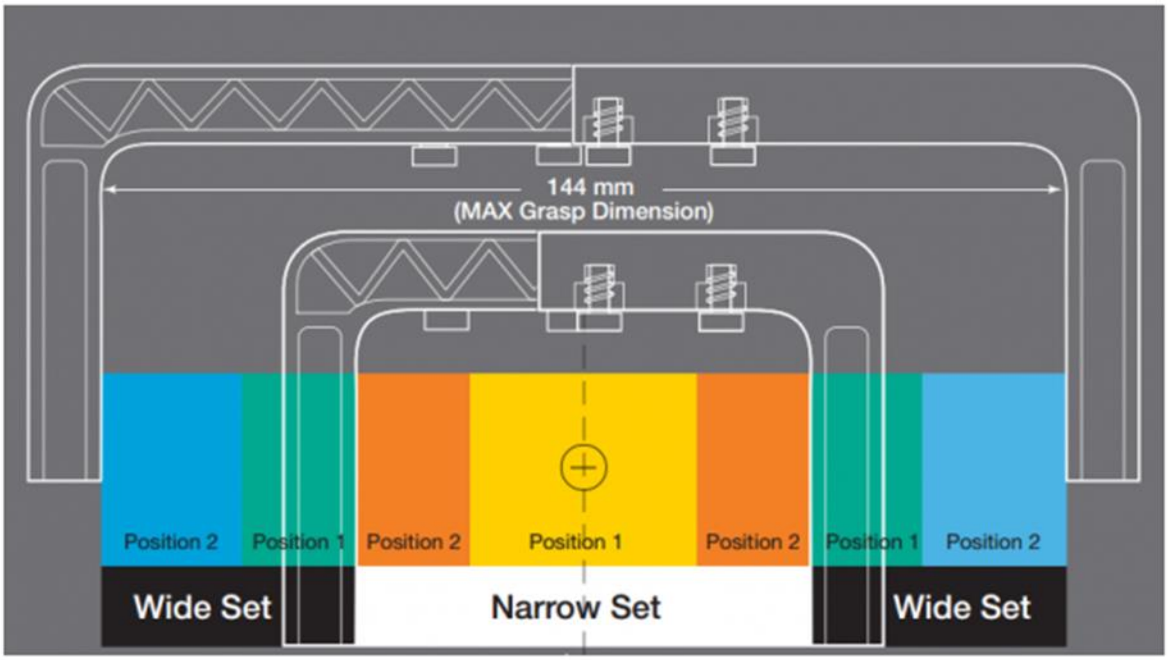
Appendix 1: Original Gantt Chart



Appendix 2: Post Campus Shutdown Gantt Chart



Appendix 3: Final Gantt Chart



Object Grasp Width	Finger	Position
0-34 mm	Narrow	1
34-68 mm	Narrow	2
68-102 mm	Wide	1
102-144 mm	Wide	2

Appendix 4: Gripper Specifications (Rethink Robotics, 2015a)