RESEARCH AND CONCEPT DESIGNS

Sustainable Engineering Design – NG2S213

Abstract

This report details research conducted into homemade and industrial-grade robotic arms. From this research, a design specification is outlined for a bench-mounted robotic arm. Using the design specification, several design concepts are then detailed, evaluated and discussed.

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Contents

Introduction

Design Brief
"Many hobbyists design and build their own robotic arms. These are then used to manufacture parts for their projects in various materials. Initial thoughts are to design and produce a home-made robotic arm using as many off-the-shelf components as possible that could be sold as both a finished product and in-kit form."

Robotic Arms in Industry

Robotic arms are widely used in industry to perform a range of tasks including welding, material handling, packing, painting, and assembling. The most common types of robotic arms used in industry are Articulated, SCARA (Selective Compliance Assembly Robot Arm), Delta, and Cartesian. These types vary according to factors such as their degrees of freedom, industrial application, and architecture.

Articulated Robots

Articulated robot arms contain links assembled in series that are connected using rotary joints, giving them a spherical workspace. The number of joints varies per the application, however, the most common used in industry allows for movement in 4 or 6 axes. This higher degree of freedom versus other types of robots makes articulated robots a common choice in most industrial applications. Figure 1.1 shows an example of a 6-axis articulated robotic arm design and Figure 1.2 shows an example of this used in industry.

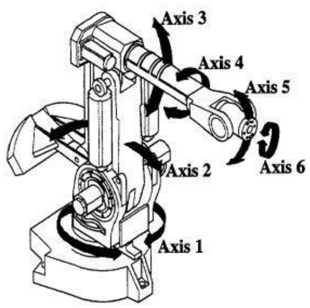


Figure 1.1: 6-axis design. *(Source: http://www.leadsingh.com/index.php/2016/09/09/six-axis-industrial-robot-india/)*

Figure 1.2: Staubli RX160. *(Source: https://www.staubli.com/en/robotics/6-axis-scara-industrial-robot/medium-payload-6-axis-robot/6-axis-industrial-robot-rx160/)*

SCARA Robots

SCARA robots are assembled, like articulated robots, using serial architecture, however, unlike articulated robots, rotation in the z-axis is fixed. This rigidity in the z-axis allows for high speed and accurate movement in the x-y plane, making SCARA robots suitable for assembling, handling, and surgical applications. They have 4 degrees of freedom, giving them a cylindrical workspace. Figure 1.3 shows an example of a SCARA robot design and Figure 1.4 shows an example used in industry.

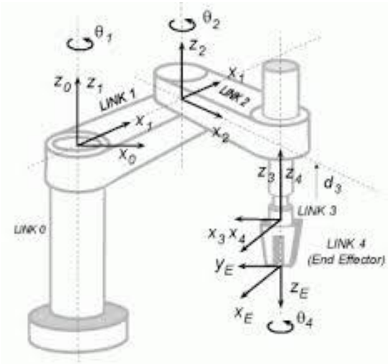


Figure 1.3: SCARA design. *(Source: https://www.linkedin.com/pulse/new-era-scara-michael-ouren)*

Figure 1.4: Staubli TP80. *(Source: https://www.staubli.com/en/robotics/6-axis-scara-industrial-robot/low-payload-6-axis-scara-robot/fast-picker-tp80/)*

Delta Robots

Unlike the previous two examples, delta robots have a parallel architecture. The motors are fixed at the base, with separate linkages connecting the base to the claw. The claw operates in a hemisphere shaped workspace underneath the base and has 3 to 6 degrees of freedom, depending on the design of the end effector. This allows high speed, high acceleration and use of lightweight materials for the linkages as the increased inertia caused by movement of heavy motors is reduced. Figure 1.5 shows an example of a delta robot design and Figure 1.6 shows an example used in industry for picking, packing and assembling.

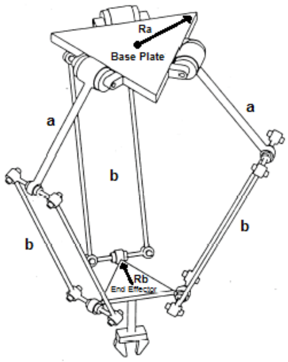


Figure 1.5: Delta robot design. *(Source: http://www.elmomc.com/capabilities/6.GMAS%20Multi%20Axis%20 Motion/12.GMAS%20Delta%20Robot/GMAS-Delta-Robot.htm#page=page-1)*

Figure 1.6: Fanuc M-3iA/6A *(Source: http://www.fanuc.eu/se/en/robots/robot-filter-page/m3-series/m-3ia-6a)*

Cartesian Robots

Cartesian robots are limited to linear translations in the x, y and z axis only. They contain no rotary joints giving them only 3 degrees of freedom and a box shaped workspace. Examples of this type of robot used in industry include CNC machines and 3D printers. They provide increased accuracy and repeatability with their simplified design. Figure 1.7 shows an example of a cartesian robot arm design and Figure 1.8 shows an example used in industry.

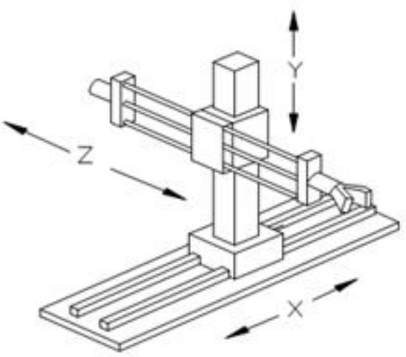


Figure 1.7: Cartesian robot design. *(Source: http://robohub.org/how-many-axes-does-my-robot-need/)*

Figure 1.8: Toshiba BA-III Series *(Source: http://www.directindustry.com/prod/tm-robotics/product-20959-1888070.html)*

Homemade Robotic Arms

As with industrial robots, homemade robots vary in their types depending on their degrees of freedom, application, and architecture. The most common type of homemade robotic arm seems to be the articulated robot due to the increased workspace for its size, and its aesthetic and structural similarities to a human arm. Below is research conducted into two different homemade articulated robotic arms.

Dobot Magician

The first robotic arm is the Dobot Magician, shown in Figure 2.1. This was a project successfully funded on Kickstarter in 2015 and is now sold as a complete product (Figure 2.2).

Figure 2.1: Dobot v1 *(Source: https://www.kickstarter.com/projects/dobot/dobot-robotic-arm-for-everyone-arduino-and-open-so)*

Figure 2.2: Dobot v2 *(Source: https://www.seeedstudio.com/Dobot-Magician-Advanced-Educational-Plan-p-2700.html)*

The design uses a motor in the base to rotate the whole arm about the z axis, two motors in the arm's first joint, and one for the pinching of the claw. The two motors connected to the first joint control movement in the first and second joints separately by connecting one of them to the second joint using a lever-based system within the framework of the arm as shown in Figure 2.3 and Figure 2.4. This allows the second joint's motor to be placed at the base of the arm, as opposed to attaching it directly to joint, reducing the inertia of the system and the load on the arm. A similar system of linkages allows the end effector to maintain parallel to the surface without the use of a motor.

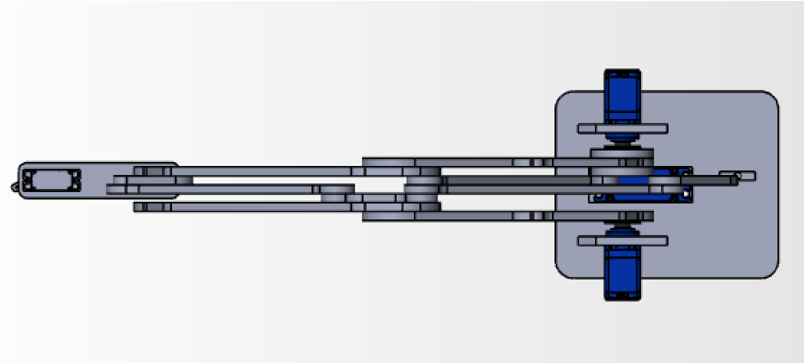


Figure 2.3: Dobot CAD model, top view *(Source: https://grabcad.com/library/dobot-4)*

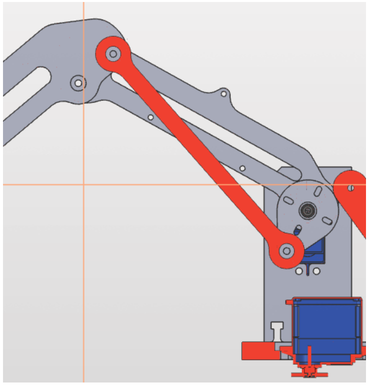


Figure 2.4: Dobot Lever System, section view *(Source: https://grabcad.com/library/dobot-4)*

The joint motors used are stepper motors. They provide superior performance at medium to low torque at a lower cost than servo motors, which is optimal for this product's home use applications. However, for increased speed or an increased payload, servo motors would be favourable.

The linkages' frameworks consist of thin, parallel aluminium pieces making them lightweight and low cost. The orientation of the outer pieces means that the forces acting on them from the weight of the arm act in a direction normal to their thinner surface. This maintains the structure's strength while reducing the amount of material needed.

The base of the finished product is non-bolted, making it easily transportable. However, this feature means that the base must have an increased weight and footprint to maintain stability and prevent the arm from tipping.

The end effector has interchangeable heads allowing different operations for a variety of applications. These include drawing, laser engraving and 3D printing.

The finished product can be controlled using devices such as PCs, phones and hand motion sensors. This variety allows for more applications and gives users a choice of preferred control.

Figure 2.5 shows the final product specifications for the Dobot Magician. The number of axes provides adequate degrees of freedom for drawing, laser engraving and 3D printing. The maximum payload and reach allows it to perform simple desktop pick and place tasks. The net weight is low enough so that users can move the product without excess effort. Overall the product is well suited to a number of home applications.

Specifictions	Number of Axes	4
	Payload	500g
	Max. Reach	320mm
	Position Repeatability(Control)	0.2 mm
	Communication	USB / WIFI / Bluetooch
	Power Supply	100 V - 240 V , 50/60 HZ
	Power In	12 V / 7A DC
	Consumption	60W Max
	Working Temperature	-10°C - 60°C
Physical	Net Weight	3.4KG
	Gross weight (Standard Version)	7.2KG
	Gross weight (Education Version)	8.0KG
	Base Dimension(Footprint)	158mm × 158mm
	Materials	Aluminum Alloy 6061, ABS Engineering Plastic
	Controller	Dobot Integrated Controller
	Robot Mounting	Desktop
	Packing Size (L × W × H)	307mm × 224mm × 330mm
	Carton Size for Standard Version (L × W × H)	340mm × 300mm × 400mm
	Carton Size for Education Version (L × W × H)	345mm × 290mm × 485mm

Figure 2.5: Dobot Magician Specifications *(Source: http://www.dobot.cc/dobot-magician/specification.html)*

PhantomX Reactor

The second robotic arm is the PhantomX Reactor shown in Figure 2.6 and Figure 2.7. This arm is made by Trossen Robotics and is available to buy in kit form for home assembly.

Figure 2.6: PhantomX Reactor *(Source: http://www.trossenrobotics.com/p/phantomx-ax-12-reactor-robot-arm.aspx)*

Figure 2.7: PhantomX Reactor *(Source: http://www.trossenrobotics.com/p/phantomx-ax-12-reactor-robot-arm.aspx)*

This design uses a motor combined with a ball bearing base to rotate the arm about the z axis, two motors in the arm's first and second joints, one in the wrist joint, and an additional two for claw rotation and grip. The use of two motors in second joint allows this arm to deal with an increased payload and to manage the weight of the additional rotational motor attached to the claw. However, these additional motors add to the arm's weight and inertia, and therefore require additional framework to support them. This increases the overall weight of the arm further, as well as increasing the cost of material and cost associated with a higher number of motors.

The type of motors used are servo motors. These allow high torque and high acceleration applications but at a higher cost than stepper motors. They also often require the use of additional equipment such as position encoders, increasing production complexity and equipment cost.

The framework of the first link, connecting the base to the second joint, is wide and box shaped with holes strategically cut to reduce its weight while maintaining its strength. The second link begins, similarly to the Dobot's framework, with two thin, parallel pieces attached to each motor. It then uses a trapezium shaped box to narrow its dimensions, transferring from the use of two motors to one. This framework gives the arm increased strength and stability, but also increases weight and cost as mentioned above.

The base of the arm requires bolting to a surface. This reduces the user's ability to easily transport the product. However, it also allows the overall weight of the product and the footprint of the base to be reduced, meaning, once the product has been removed from the surface, it can be easily carried, transported and re-positioned.

The claw is primarily a two-finger gripper, ideal for pick-and-place applications. It also has a mounting bracket available for attaching additional hardware such as cameras and sensors. This enhances the gripper's possible applications by allowing it to work simultaneously with several different hardware choices.

Figure 2.8 shows the product specifications for the PhantomX Reactor. The strength of this arm is impressive considering its low weight, and should easily complete many desktop pick-and-place tasks. Its maximum reach and workspace is ideal for most home-use applications.

Reactor Arm Stats	
Weight	1360G (1430 W/ Rotate)
Vertical Reach	51CM (55.5 W/ Rotate)
Horizontal Reach	38CM (43 W/ Rotate)
Strength	30CM/200G
	20CM/400G
	10CM/600G
Gripper Stength	500G Holding
Wrist Lift Strength	250G (150 W/ Rotate)

Figure 2.8: PhantomX Reactor Specifications

Design Specification

Target Market

- The target audience for this product will be people with interests in robotics and future technology.

Function

- The product will be able to pick and place common desktop items.
- Its controls should be as user friendly as possible.
- Maximum reach will be at least 300mm with at least 180° rotation.
- Maximum payload will be at least 20g at 300mm extension.

Environment

- The product will operate indoors and therefore not require protection from any weather related environmental factors.
- It will operate at room temperature so will not require the use of any heating/ cooling systems.
- The product is designed for recreational home use, so noise production should be kept as low as possible, no more than 55 dB.
- The product is designed for desktop use, so protection from water damage at the base is advisable as drink spillages on desktops are common.

Materials

- Materials used for the linkages should be lightweight but strong enough to deal with maximum payload.
- Preferably plastic, possibly a lightweight metal such as aluminium.

Shipping

- The product will be shipped either assembled or in kit form for user assembly.
- It will be delivered in a cardboard box, packed neatly inside foam padding to prevent damage to parts.
- Instructions for use and assembly (if necessary) will be shipped with the product.
- If delivered in kit form, any small parts such as screws will be stored together in small, sealed plastic bags.

Equipment/ Tool Requirements

- If the product is shipped in kit form, assembly will be made possible using simple, household tools such as screwdrivers.
- Operating the product will require additional equipment such as a PC or laptop.

Aesthetic

- The product will be built according to an articulated (4-6 axis) robot arm's architecture.
- Internal wires can be visible but should be neatly kept within the arm's framework.

Size and Weight Restrictions

- The product will be easily transportable for use in various locations, so total weight of the product should not exceed 5kg.
- The product will be suitable for desktop use, so the base dimensions should not exceed 200mm x 200mm.
- For ease of transport and storage, the arm should fold neatly into a compact space when not in use.

Maintenance

- Regular inspection of motors for dust and debris is recommended but not essential and is the responsibility of the customer.
- Software updates and patches will be made available to download and install via the internet.

Health and Safety

- To prevent damage to property and reduce risk of injury to users, set reasonable limits to the arm's maximum speed.
- Include an emergency stop button or function to cut power in case of emergencies.

Cost

- The cost of production including all materials and off the shelf parts should not exceed £200.

Design Concepts

Each of the following design concepts contains an annotated sketch and a free body diagram. In the sketches, motors are represented as shaded boxes. The sketches are not drawn to scale, an idea of size is given by the linkage lengths in the free body diagrams.

In the free body diagrams, each joint/ motor is represented by a box with its holding torque, mass, and number of motors labelled. Below the diagrams are equations calculating the maximum payload at 300mm extension for the first, second and third joints, P_1, P_2, and P_3 respectively. The maximum payload of the arm at full extension, P_{max}, is the smallest of these values.

The calculations ignore the mass of the framework, takes one motor's holding torque to be 3.6 kg.cm, and takes one motor's mass to be 0.34 kg *(Tmart, 2017)*. The final linkage in each diagram represents the claw and is estimated to have a length of 10cm and mass of 70g *(Amazon.co.uk, 2017)*.

The purpose of the free body diagrams is to estimate each arm's maximum payload at 300mm extension. Each arm aims to have more than 20g maximum payload at this extension, as outlined in the design specification.

Design Concept 3 has an additional sketch, Figure 3.7, showing an early concept of the lever system that will connect base motors to their joints.

Design Concept 1

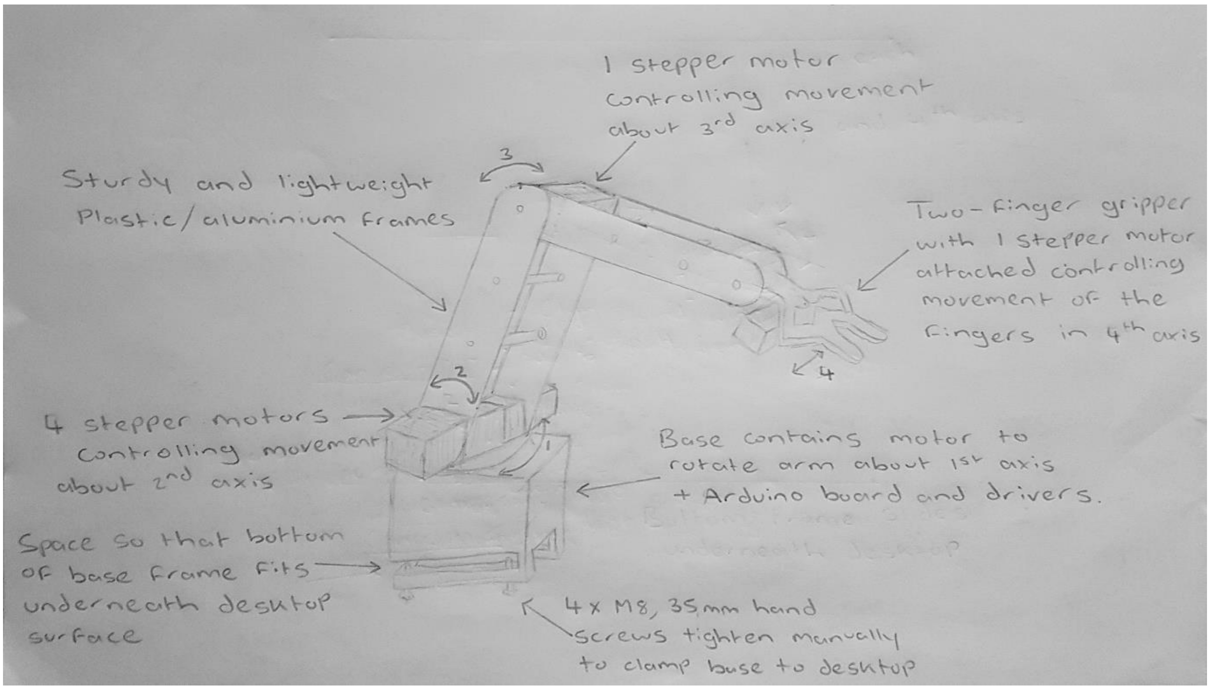
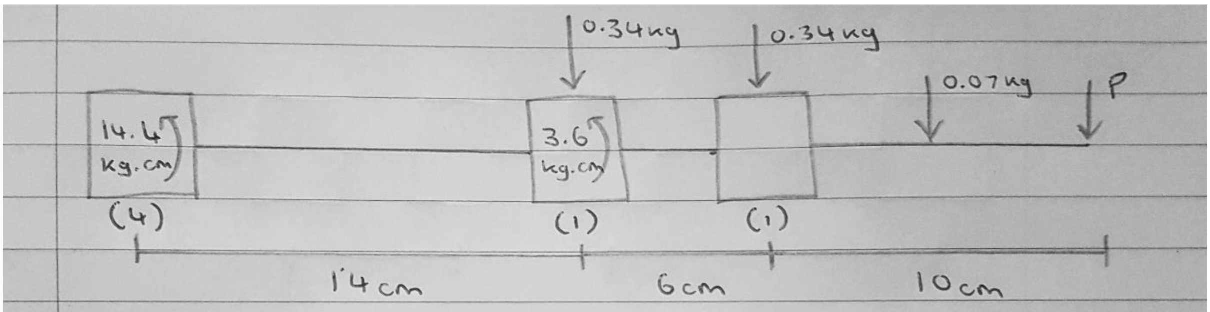


Figure 3.1



$$P_1 = \frac{14.4 - (0.34 \times 14 + 0.34 \times 20 + 0.07 \times 25)}{30} \times 1000 = 36g$$

$$P_2 = \frac{3.6 - (0.34 \times 6 + 0.07 \times 11)}{16} \times 1000 = 49g$$

$$P_{max} = 36g$$

Figure 3.2

Design Concept 2

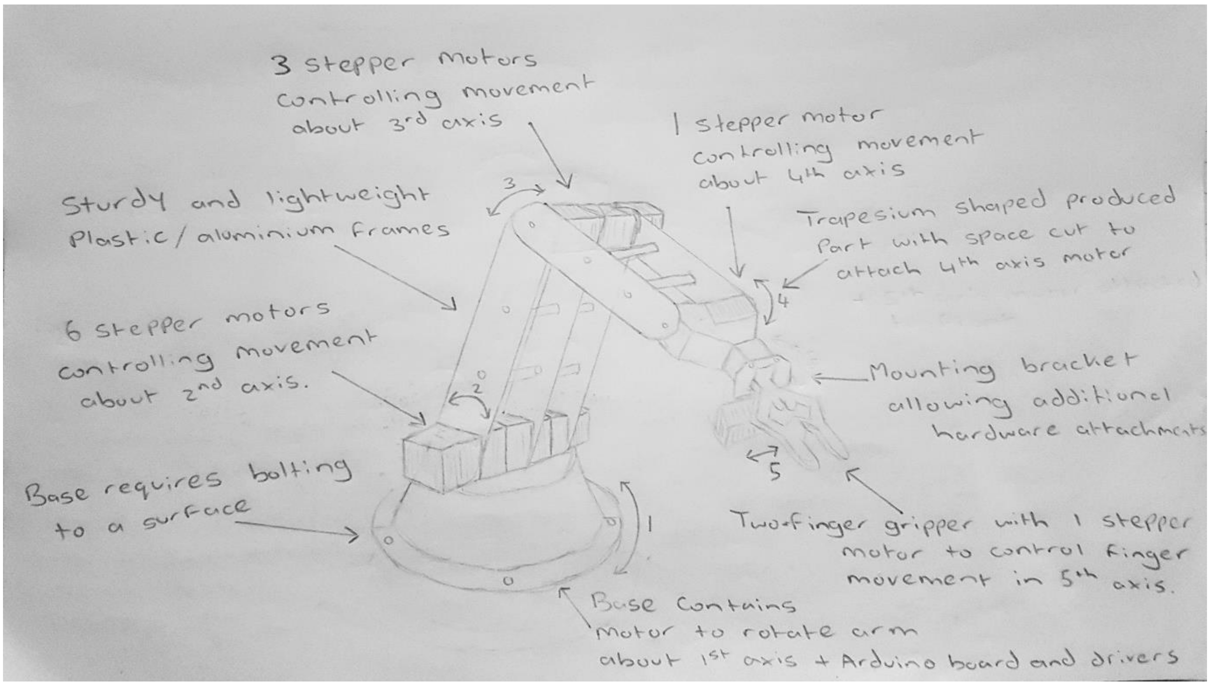
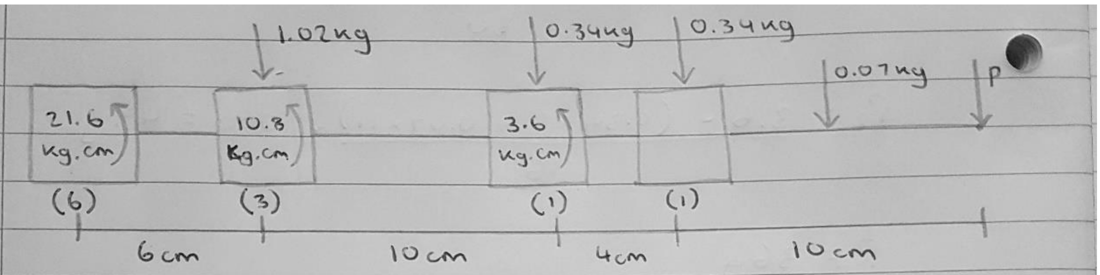


Figure 3.3



$$P_1 = \frac{21.6 - (1.02\times6 + 0.34\times16 + 0.34\times20 + 0.07\times25)}{30} \times 1000 = 49\,g$$

$$P_2 = \frac{10.8 - (0.34\times10 + 0.34\times14 + 0.07\times19)}{24} \times 1000 = 55\,g$$

$$P_3 = \frac{3.6 - (0.34\times4 + 0.07\times9)}{14} \times 1000 = 115\,g$$

$$P_{max} = 49\,g$$

Figure 3.4

Design Concept 3

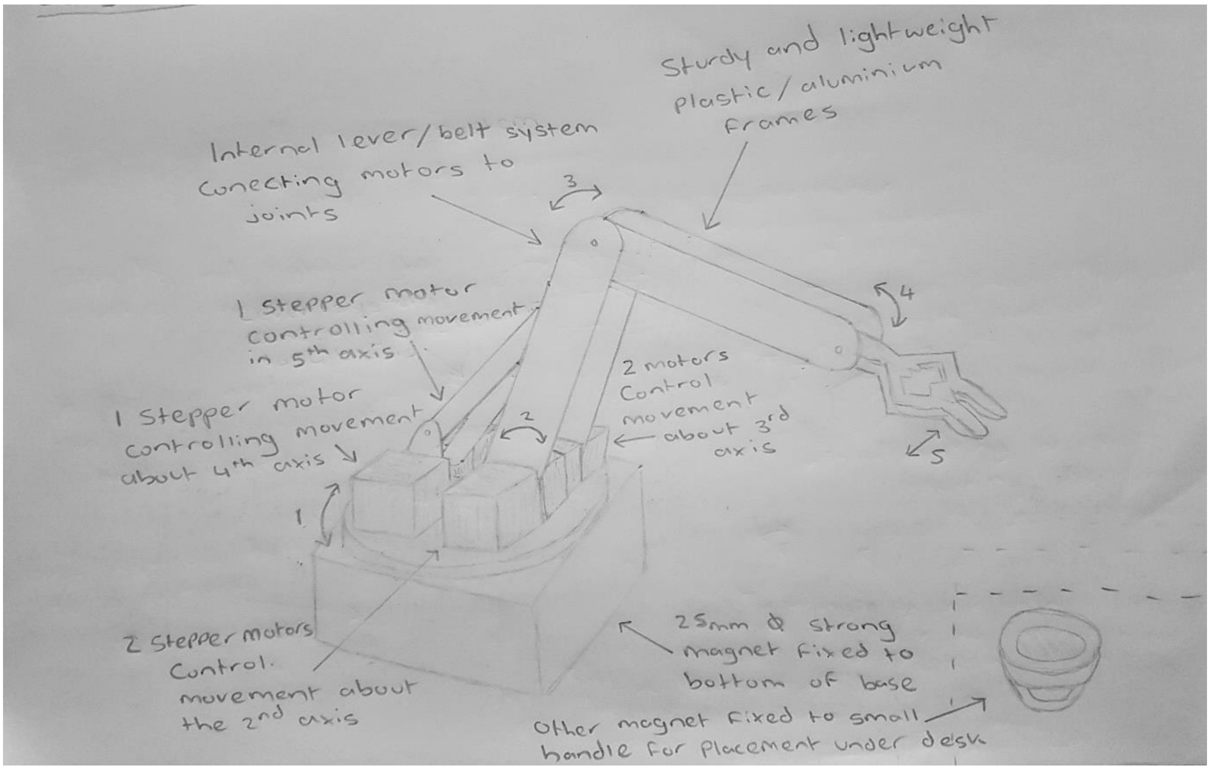
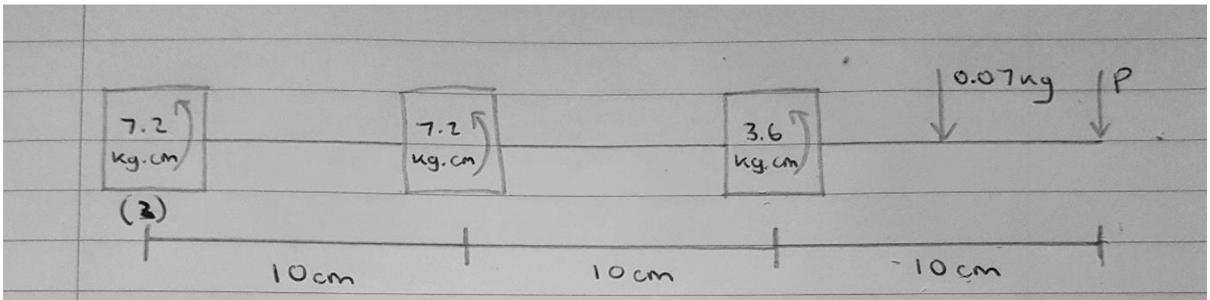


Figure 3.5



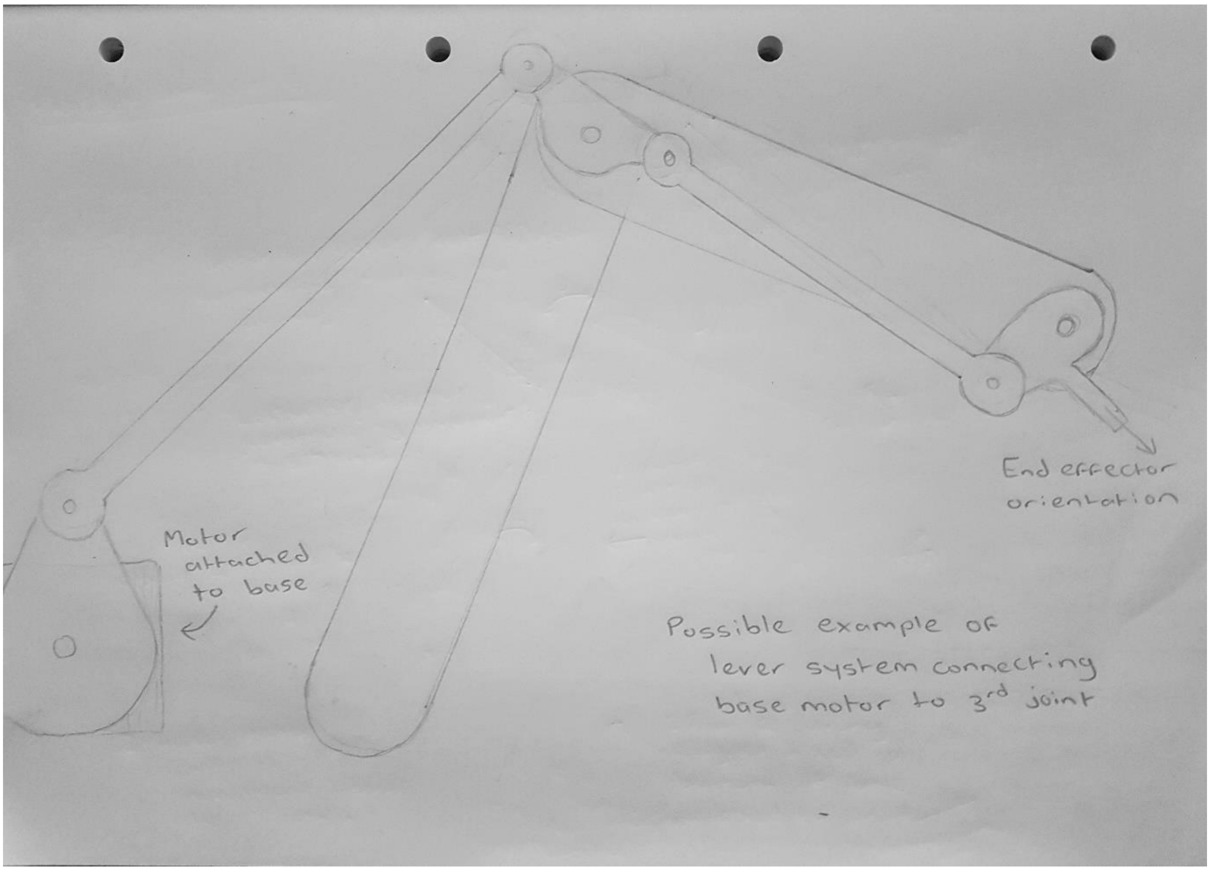
$$P_1 = \frac{7.2 - (0.07 \times 25)}{30} \times 1000 = 181\ g$$

$$P_2 = \frac{7.2 - (0.07 \times 15)}{20} \times 1000 = 308\ g$$

$$P_3 = \frac{3.6 - (0.07 \times 5)}{10} \times 1000 = 325\ g$$

$$P_{max} = 181\ g$$

Figure 3.6



End effector
orientation
Motor
attached
to base
Possible example of
lever system connecting
base motor to 3rd joint

Figure 3.7

Concept Evaluations

Design Concept 1
This design maintains simplicity with minimal use of material and parts. The framework largely consists of just two, parallel frames with added interior support. This keeps the cost of material and production of parts to a minimum while maintaining adequate strength and mobility for home-use applications.

The design uses a total of 7 stepper motors. The layout of the motors gives this design 3 degrees of freedom, along with 1 degree of freedom on the claw, enough for basic home-use applications, however, the absence of a rotary joint for the claw can make some desktop pick-and-place tasks awkward to complete. The use of four motors in the first joint supports the weight and inertia of the second joint motor and the motor attached to the claw. At 300mm extension the design's maximum payload is 36g.

The base is designed to slide onto a desktop using hand screws to clamp the frame in place. The advantages of this design are that it produces stability without a major increase to the base's weight and footprint, and it is user friendly, allowing for quick and easy re-positioning while requiring no additional tools. However, this design limits the placement of the product to the edge of a desktop only. Wall mounting, floor use, and positioning towards the centre of a desktop are not possible with this design.

The end-effector is a simple two-finger gripper available to purchase online. The absence of a mounting bracket or interchangeable heads limits the functionality of the product, but maintains its simplicity and is adequate for most home-use applications such as pick-and-place tasks.

Overall this simplistic design offers basic functionality for home-use, desktop applications with minimal use of material and produced parts. It is lightweight and easily transportable. The reduced cost of materials and production, combined with the cost of just 7 stepper motors, will allow this arm to be produced for less than the target cost of £200. However, the design is limited in its placement, the maximum payload is reduced due to the attachment of motors directly to the joints, and the absence of a rotary joint for the claw limits its possible orientations.

Design Concept 2

This design utilises more motors to allow an additional degree of freedom and the use of additional hardware. The framework is like that of Design Concept 1, with thin, parallel frames, but with additional frames used to support the three motors at the second joint and the motor at the third joint. This increases the cost of material and production of parts but also increases functionality as this design can deal with the claw's additional motor, and additional hardware attached to the end-effector.

The design uses a total of 12 stepper motors. The layout of the motors gives the design 4 degrees of freedom, along with 1 degrees of freedom on the claw. This is enough for most home-use applications and the additional degree of freedom allows for improved pick-and-place functionality. The design's maximum payload at 300mm is 49g, meaning if additional hardware is used, the design's maximum reach will likely decrease.

The design has a circular base with flat edges to allow securing to a surface. This allows the product to be securely fixed without an increase in its weight and footprint, and allows placement in many locations such as the floor, desktop centre, and wall. However, this makes transportation difficult and any placement should be permanent as it requires drilling holes in the surface to fix it in place.

The end-effector is a two-finger gripper with a mounting bracket. The mounting bracket increases this design's functionality by allowing additional hardware such as cameras to be attached and work cooperatively with the gripper.

Overall, this design allows for increased functionality by using additional motors to support increased payloads, additional hardware, and additional degrees of freedom for the claw. However, the increased functionality comes at a cost for the increase in materials used, parts produced, and number of motors used and is unlikely to be produced under the target cost of £200. The design also allows placement in many locations but makes the product difficult to transport and reposition.

Design Concept 3
This design fixes all its motors, and therefore also their weight, to its base. It uses interior lever systems, like those within the Dobot Magician, and belt systems to connect motors at the base to their desired joints. The design builds on the design of the Dobot by adding an additional motor at the base to give it an additional degree of freedom.

The design uses less framework to support moving motors, however, there is added complexity to this design and an increased number of parts need to be produced and assembled.

This design uses a total of 7 stepper motors, while maintaining mobility with 4 degrees of freedom, and 1 degree of freedom on the claw. The layout of the motors allows their weight to be maintained at the base of the product, allowing the system to deal with minimal inertia, maximising the potential payload for the amount of material and number of motors used. At an extension of 300mm, the design's maximum payload is 181g. Alterations to this design's linkage lengths and motor-joint combinations could see its payload or maximum reach increase.

The base is box shaped and contains the base motor as well as the Arduino board and drivers. It uses a pair of magnets, one fixed at the bottom of the base, and the other placed underneath a surface by the user in their desired placement location. The magnetic attraction produces a downward force on the base, allowing increased stability with a reduced weight and footprint. Like the clamp design in Concept 1, this design allows easy placement and repositioning making the product easily transportable. Unlike Concept 1, this design allows placement away from the desktop edge and, with a magnet strong enough, opens the possibility of floor and wall mounting with magnetic surfaces. Possible limitations to this feature include safety risks to the user, with the use of strong magnets posing the risk of catching body parts such as fingers. Its effect is limited when the thickness of the surface is increased, and there is the possibility of interference with metallic desktop items and other metallic surfaces.

The end-effector is a simple two-finger gripper, similar in design and functionality to Design Concept 1.

Overall this design allows adequate functionality for home-use, desktop applications with reduced use of material. It is lightweight, easily transportable and has many possible placement positions. The reduced cost of materials, combined with the cost of 7 stepper motors, should allow this arm to be produced for less than the target cost of £200. The fixing of motors at the base increases the maximum payload. However, the added complexity of this design requires more parts to be produced rather than using off-the-shelf components, the absence of a mounting bracket for the end effector limits its functionality, and the use of a magnetic base poses safety issues for the user.

Concept Discussion

Each concept has the potential to meet the requirements outlined in the design specification, while each having their own advantages and disadvantages. To compare the design concepts effectively, the design criteria have been split into three separate categories, Production and Materials, Functionality, and User Experience. Each of the categories have been given a weighted decision matrix to compare their elements in detail. The final weighted decision matrix discusses the relative importance of each category to give an overall score to each design concept.

For each decision matrix a percentage weighting is used to compare the relative importance of the design criteria. Each concept is then given a score out of 5 for each design element, 5 being the greatest and 1 being the poorest. The scores and weightings are combined to give each design a percentage score for each category and an overall percentage score.

Production and Materials				
Criteria	Weighting	Concept 1	Concept 2	Concept 3
Number of Motors	30%	4	2	4
Production of Parts	30%	4	3	2
Material Costs	30%	4	2	3
Ease of Assembly	10%	4	3	2
Total	100%	80%	48%	58%

Figure 4.1

Functionality				
Criteria	Weighting	Concept 1	Concept 2	Concept 3
Degrees of Freedom	35%	2	4	4
Additional Hardware Integration	15%	1	4	1
Max Payload at Extension	25%	2	2	4
Potential Max Reach	25%	3	3	4
Total	100%	42%	65%	71%

Figure 4.2

User Experience				
Criteria	Weighting	Concept 1	Concept 2	Concept 3
Safety	30%	3	3	2
Transportability/ Storage	25%	4	2	5
Aesthetic	20%	2	3	4
Footprint	25%	2	3	3
Total	100%	56%	55%	68%

Figure 4.3

Overall				
Category	Weighting	Concept 1	Concept 2	Concept 3
Production and Materials	40%	80%	48%	58%
Functionality	30%	42%	65%	71%
User Experience	30%	56%	55%	68%
Total	100%	61.4%	55.2%	64.9%

Figure 4.4

For the “Production and Materials” category, Ease of Assembly was weighted lower than other criteria as it forms a lower proportion of overall cost of production and there is the option of selling the final product unassembled in kit form.

For the “Functionality” category, Degrees of Freedom have an increased weighting due to their importance in performing desktop pick-and-place tasks. Additional Hardware Integration has a lowered weighting as it is an advanced feature, not essential for most home-use applications.

For the “User Experience” category, Safety’s weighting was increased to represent the moral and financial importance of ensuring customer safety.

For the “Overall” decision matrix, Production and Materials was awarded the highest weighting due to the bottom line being the financial aspect of the design.

Conclusion

The design concept evaluated as having the highest overall score, and therefore concluded to have the greatest potential, is Design Concept 3. The objective going forward will be to design, in detail, the interior workings of this concept and make alterations to the design if necessary, including linkage lengths and motor set up, to maximise potential reach and payloads. If, however, this concept fails, Design Concept 1 scored a close 2nd and would make a suitable substitution.

References

Tmart. (2017). *JKM JK42HS48-2504 42mm Hybrid Stepper Motor 70oz-in 48mm 2.5A for CNC*. [online] Available at: http://www.tmart.com/JKM-JK42HS48-2504-42mm-Hybrid-Stepper-Motor-70oz-in-48mm-2-5A-for-CNC_p350484.html [Accessed 1 Nov. 2017].

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