ROCO507: Advanced Robot Design And Prototyping.

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1 Abstract

This report displays the creation of Traybot. It incorporates the design process as well as simulation to present the proof of concept. The Traybot is a logistics robot which is to be used in healthcare, its primary function is to deliver food or oral medication to a patient in quarantine. A secondary function is to filter and clean air with an inline air filter. This report will cover the mechanical components for each key part of the design, such as linear actuators, belt drives and the system incorporated into the wheelbase. Justification will also be given for all the decisions made during the design process. CAD models, Simulation and other supporting software is avialable on **Github**.

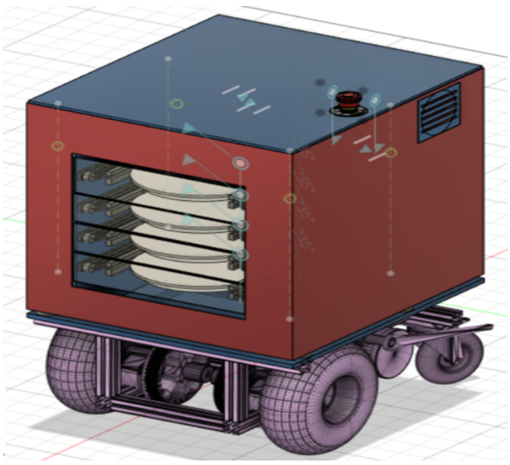

Figure 1: The Traybot

2 Introduction

The British Medical Journal recently published a report stating that "hand-mediated transmission is a major contributing factor in the acquisition and spread of infection in hospitals, and such transmission can occur directly via hands, or indirectly via an environmental source"[1]. Furthermore, it has been found that hand contamination with MRSA occurs as often when healthcare staff touch contaminated surfaces as with direct contact with an infected patient [2]. An approach to reducing these healthcare acquired infections (HCAIs) could be to find better methods of decontaminating frequently touched surfaces. However, it also raises the question "is it possible to reduce the number of surfaces which need to be touched by multiple people?". In this work, we seek to explore this possibility by designing Traybot, a robot capable of completing routine hospital logistics autonomously.

3 Literature Review

The concept of using autonomous robotic couriers within hospitals is not new, an early implementation was trialled in 1991 [3]. Named Helpmate, the authors produced a mobile platform which relied on a fusion of structured light, ultrasound and contact bumpers to navigate whilst avoiding collisions. The robot could be dispatched using a screen and keypad, and upon arrival at its destination payloads were manually unloaded. The use of a voice output system to narrate robot behaviour was considered crucial in gaining acceptance within the hospital. Although great potential was shown, the authors concluded that future developments would benefit from advances in sensing and processing technology.

A similar concept was more recently reported in 2015: the hospital mobile platform [4]. Additional power management features were included, such as regenerative braking and autonomous changing via a docking bay. To provide the manoeuvrability needed to avoid collisions in a hospital setting several drive systems were considered. Omni-wheels were rejected due to noise concerns raised by the hospital staff, and a differential drive with four powered wheels was chosen. Since the platform was required to move packages between defined stations, a laser range finder was used to map and localise the platform within its environment. As with the Helpmate, items had to be manually loaded and unloaded. The authors noted that their system could also be appropriate for use in other sectors such as mail delivery and grocery shopping.

To this date, we are unaware of any logistics robots that have been trialled transporting items in a hospital setting without requiring human contact for loading or unloading. However, this capability has already been implemented in other sectors. Geek+ [9] are a global technology company which specialise in robotics. They solve robotics problems involved in warehouse environments which include picking, moving, fork lifting and sorting. In the interest of collecting and depositing boxes within a warehouse, the model C series has been of great interest to this project. It involves a unique telescopic mechanism for collecting items, which is how we were inspired for the final design of our own tray mechanism.

Safety is of great importance, since we are interested in a hospital setting this factor is paramount. Simple solutions such as the emergency stop button located on the top of our robot can help reduce the cause of harm to patients and hospital staff. One issue which has been investigated in the past and which is to be utilised in our design is the use of a UVC lamp in the air filtration system. It has been reported that "UVC exposure is unlikely to cause acute or long-term damage to the skin but can cause severe acute damage to the eye"[11]. UVC lamps do however emit small levels of UVB radiation and therefore exposure to very high doses or low prolonged doses can contribute to the effects of skin cancer, short term skin irritation and short term breathing issues [10]. Therefore any UVC lamps must not come into contact with human skin, or be visible to people nearby.

4 Design Process/Implementation

From the start of the project many ideas/mechanisms of the Traybot have evolved or changed completely over time. In order to achieve the functionalities of the Traybot specific goals had to be met. These goals include; creating a mechanism which allows the robot to move vertically in order to reach to different table heights, create a tray mechanism which retrieves as well as dispenses trays, create a wheelbase which can cope with a smooth floor surface but will also allow the robot to be as agile as possible and finally to create a simple air filtration system.

The design process of each component would evolve based on feedback given through the preliminary and critical design review (PDR/CDR). Each component would also be improved based on research, as well as alternative methods used in previous applications.

4.1 Vertical mechanism

In order to raise the main body of the robot which would then allow access to a variety of table heights a mechanism with precision is needed. The initial idea was a scissor lift mechanism seen on many forklifts, it is a simply idea which is compact, robust and reliable. This initial idea was soon changed due to a centre of mass issue. If the robot were to be extended to its maximum height then the centre of mass will shift causing the robot to become unstable and could cause it to possibly tip over. This is highly undesirable and can be a safety issue to patients and hospital staff.

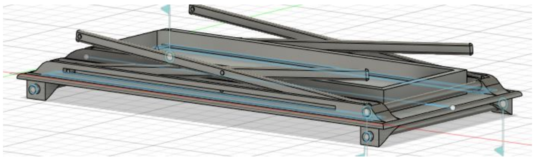

Figure 2: Scissor lift mechanism

After evaluation of the scissor lift method we decided to change to a rack and pinion linear actuator, this will give the torque required to lift the Traybots main body which houses the trays as well as the air filter. Positioning one in each corner will remove the previous issue which the scissor lift mechanism had as the centre of mass will only shift vertically by a slight amount. Other methods such as lead/ball screws have also been researched but were not chosen due to the lack of rigidity compared to a rack and pinion. A lead-/ball screw option also create a screw whip issue, this is were vibrations occur due to high speeds over long axis. This causes a inaccuracy, which for precision work is undesirable. Other reasons for using a rack and pinion method are because of higher reliability in harsher environments and extremely efficient transfer of power compared to lead screw method.

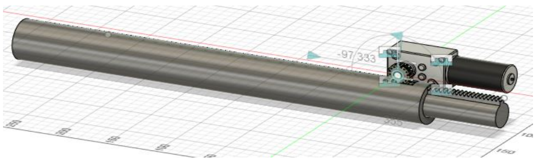

Figure 3: Rack and pinion linear actuator

4.2 Tray mechanism

The tray mechanism has a few different part which have been developed and added over time. The first mechanism needed is one in which extends the tray, the second is the tray mechanism which allows efficient delivery and collection of trays. The first concept was to create a belt drive that spans the width of the tray and a forklift tray mechanism which moulds to the shape of a square tray. This was a good first concept but had a few issues which needed to be improved in order to make is more efficient. The first issue was the yaw orientation of the tray itself. If the tray is sitting at an awkward angle when being collected then this creates a meshing problem. To over come this a more symmetrical tray was created, this was the shape of a disk which had a small flat lip which could be used to support the try when it is being collected. The belt drive was also replaced as when fully extended the weight which sits a the furthest point from the robot could cause a jamming issue.

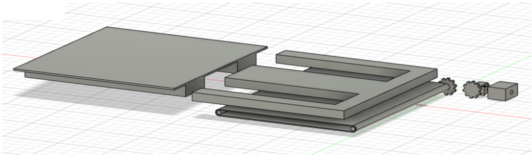

Figure 4: Forklift tray mechanism

This was replaced with a rack and pinion method as is rigid enough to cope with heavy trays when fully extended and is incredibly precise. This rack and pinion would sit on rails which guides the tray mechanism in and out of the robots main body. So when the tray mechanism is extended the negative mould would scoop up the tray and therefore the tray would be retrieved. The next problem was a reliability issue, if the tray were to be overloaded at the far end then it would tip and fall out of the tray mechanism. This called for an adaption of the tray shape and the mechanism itself. At this point another problem was also spotted, the rack and pinion was a great method to extend the mechanism however the rails which would guide the tray mechanism would limit the reach to just outside the robots main body.

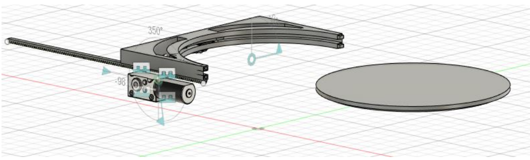

Figure 5: Rack and pinion tray mechanism

These problems were overcome with a bit of ingenuity. Firstly the tray mechanism, an embedded rim was placed on the tray which allowed it to be hooked onto when sitting inside the tray mechanism. When the tray is seated correctly a servo motor rotates a small horn which locks the tray into place. A curved rail has also been added which extends around the lip of the tray to give it extra support, for scenarios where the trays load sits outside of the centre point. As for the extension and recall of the tray mechanism, this was changed to a telescopic design and the initial idea of using a belt drive was reused. A linear guide bearing rail is used on each side of the tray mechanism and is what connects the tray mechanism to the main robot body. These highly precise and rigid rails use linear bearings which are designed to utilise the motion of rolling elements which are perfect for high load cases. The block on these linear rails then attach to a aluminium extrude which guides the carriage plate which is connected to the tray mechanism. The linear rails and carriage plate are moved forwards and backwards via individual belt drives each powered by a stepper motors.

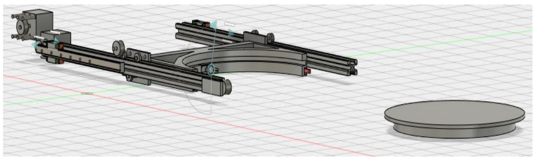

Figure 6: Final tray mechanism design

4.3 Wheelbase

4.3.1 Initial considerations

The robots mobile base needs to satisfy many requirements. It must fit within a footprint of around 0.5m squared, permitting navigation though narrow corridors. It must be highly manoeuvrable, as the wheelbase is used to align the tray mechanism. To keep the overall centre of mass low, the wheelbase must be of minimal height, and house heavier components such as the battery.

To provide maximum agility, only holonomic drivetrains were initially considered. A powered castor vehicle (PCV) [5] drive was originally intended, but rejected due to the complexity of additional steering motors and concerns about stability when specifying a new vector of motion [5]. The use of an omni-wheel drive was also explored. However, this approach forbid the use of inflatable tyres, losing advantages they provide, such as better grip and an inherent suspension. These factors, in addition to the previously discussed noise concerns, prompted us to reevaluate whether a fully holonomic drivetrain was essential. We concluded that a simple differential drive could adequately balance our various requirements. Although lateral movement is denied, zero radius turns and the use of conventional tyres is possible. Another benefit is that this drivetrain is already commonly accepted within hospitals for electric wheelchairs. Subsequent design of the mobile base used these as a starting point, with two powered front wheels and two idling castor wheels at the rear.

The computer aided design (CAD) package Solidworks 2016 was utilised for modelling of the mobile base. Figure 7 shows an early design, 30x30mm RS-Pro aluminium extrusion provides an easily assembled rigid framework. Toothed belts couple DC motors to the driven wheels, allowing for quiet running and the possibility of regenerative braking. Custom components, such as mountings and pulleys are designed for manufacture by fused deposition modelling (FDM) 3D printing.

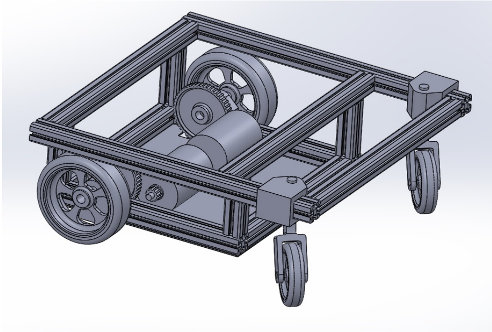

Figure 7: Early mobile base design

A safety issue became apparent: the back-drivable drivetrain presents a risk of uncontrolled motion in the event of power failure.

4.3.2 Final design

The final design is shown in figure 8, and uses dimensionally accurate available components, which are specified in appendix 9.2. To solve the back-driving safety issue, the use of a worm reduction was considered instead of a belt drive, but the addition of a dedicated fail-safe braking system was preferred. This gives the advantage of allowing back-driving during normal operation. Highlighted in blue, the fail-safe brake acts directly on the tyres, so that the base can still be bought to a stop in the event of a belt failure or a wheel becoming decoupled from its pulley.

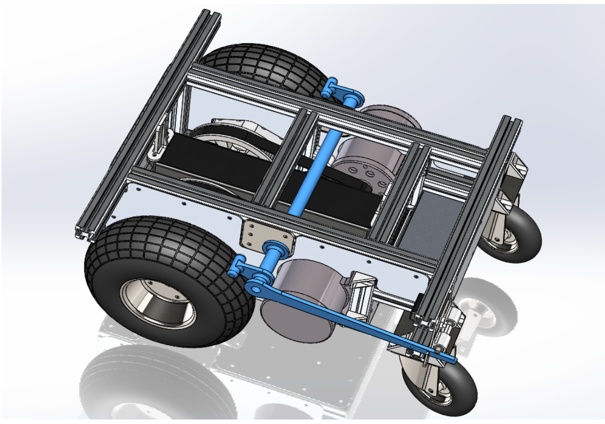

Figure 8: Final mobile base design

Braking force is provided by a powerful tensioned spring hooked on the main body, raising the pivoting arm. The pivoting arm is secured by a sprung sliding pin, held in place by a small servo, which requires continuous power to prevent retraction of the pin. The system is reset manually by pressing down on the pivoting arm. Should the Traybot need to be moved without power fail-safe can be disabled by unhooking the sliding pin spring.

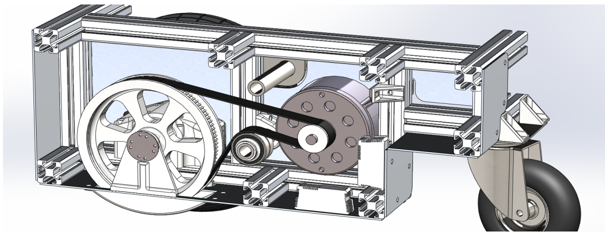

Figure 9: Cross section

As shown in figure 9 belt tension is applied by vertically adjusting a bar which spans the width of the frame. Quadrature encoders give 1200 pulses per revolution of each driven wheel shaft, allowing motion control to within 0.7mm. At peak motor power, the 1:5 belt reductions give 13.9N/m torque at 550rpm for each wheel. This translates to a robot velocity of 7.48m/s, and acceleration of 2.009m/s^2 on level ground, using an estimated total Traybot weight of 106.4kg. As DC motor stall torque is usually greater than peak power torque, the capability for greater acceleration is expected at lower speeds. The calculation of these values is given in 9.3.

4.4 Air filtration system

Air filtration was not the primary task for this project. This being said we though it would be beneficial as a secondary task. Implementing an inline filtration mechanism within the robot will allow air filtration as the robot moves around the hospital. Infectious diseases (such as COVID-19) was the inspiration for this project and by reducing the contact between nurse/-doctor and patient is of great importance. Therefore having an air filtration mechanism to clean the air around the patient is highly desirable as reduces the risk of air born transmitted diseases to others.

Initially, the idea of the air filtration mechanism involved two propeller-like fans which draw air in to a chamber where is it then sanitised with a UVC light. The idea was to have the first propeller moving at a faster RPM compare to that of the second, therefore creating a stagnant pocket of air. The stagnant air then has more time to be sanitised by the UVC lamp before it is expelled back into the environment. However, the stagnant pocket of air causes high pressure which can sometimes cause issues by restricting air flow.

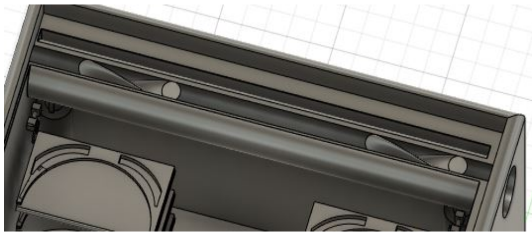

Figure 10: Initial air filter involving 2 propellers.

Due to the main problem being the higher air pressure between the two propellers the initial design was changed to incorporate a circular filter with two intake fans which create low pressure therefore sucking the air in by creating a vacuum. The idea of using a UVC light still remained by threading it through the centre of the air filter.

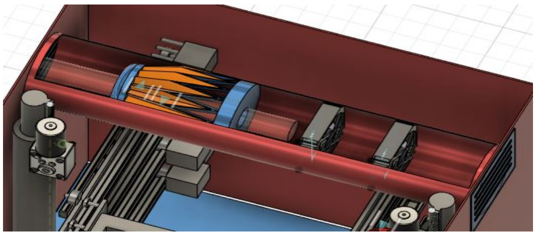

Figure 11: Final air filter design.

After researching into how harmful UVC lamps can be, the design had to incorporate a level of safety in order to prevent contact with human skin. For this reason the UVC lamp exists in a closed region which is the tube that houses the components of the air filter. It has no open links to the rest of the internal components of the robot. The only opening is at each end of the air filtration system which allows for the intake and outtake of air. These openings are covered using vents to prevent UVC light leaking out of the system but allows air to pass through the system.

4.5 Control and sensing

In this work, our efforts have mainly focused on mechanical considerations. However, the Traybot is intended to navigate and complete tasks autonomously, so it must be able to perceive its environment. This will be mainly provided by an RGB-D camera. However, we intend to include a 2D lidar, ultrasound, and bumper switches as redundant sensors to permit safe operation under poor sensing conditions. Integration of sensor data with high level software such as simultaneous localisation and mapping (SLAM), path planning, and visual servoing will depend on the Robot Operating System (ROS) [7]. Although SLAM incurs a significant computational burden, it can still be made to work well on a Raspberry Pi 2 Model B[6]. More recent models include WiFi and Bluetooth connectivity, in addition to faster processing [8]. For these reasons, we propose the use of an on board Raspberry Pi 4 for autonomous operation. This may also act as a TCP/IP server, potential allowing remote control and monitoring from several desktop or mobile devices. It's computational burden may also be reduced by adding peripheral microcontrollers for basic tasks such as stepper motor control.

In the busy environment of a hospital, it is essential to follow a path which copes for a highly dynamic environment. In order to do this, SLAM along with a neuro-evolution multi-layer perception (MPL) based controller [12] can be combined, creating a NeoSLAM, [13] method of navigation. The use of motion sensors for example, can be placed in corridors of hospitals. These will provide data as to how much traffic is in that area, this will contribute to the decision of determining the best possible path for the robot to take and has a secondary feature of allowing cleaning staff to know the high traffic areas which can be deep cleaned.

5 Experiments

5.1 Simulation

To verify the practicality of our design choices, the physics-based robot simulator CoppeliaSim was used at various stages throughout the project. It was anticipated that reliably securing trays from surfaces would present the greatest risk of project failure. Therefore early trials did not include visual representations of the Traybot, using only basic kinematics and primitive objects to test tray-robot interactions.

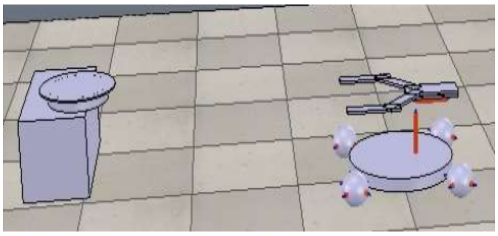

Figure 12: Early simulation

As shown in figure 12, a holonomic drive is used, which gave easy adjustment of the Traybots pose under manual key control. As intended, the use of a circular tray facilitated picking by allowing potential approaches from numerous directions. However, it became obvious that a mechanism was required to lock the trays in place to prevent them from slipping or tilting.

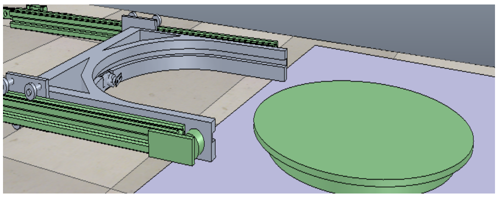

Figure 13: Securing trays

As shown in figure 13, a grasping mechanism was designed using a slot to prevent trays from tilting, with the addition of a clamp driven by a small servo to lock them in place. However, this interface required high accuracy to properly align, and trays were more often pushed away from the Traybot than secured correctly.

The mobile base was updated to use a differential drive, which gave adequate adjustment under manual control, but required more forethought for in obtaining poses since lateral motion is no longer possible. The grasping mechanism was modified to allow more reliable capturing of trays, especially with poor alignment. A servo actuated rotating hook was found to work well, which serves the dual purposes of sliding the tray into place, and then securing it in position. Figure 14 shows the successful capture of a tray.

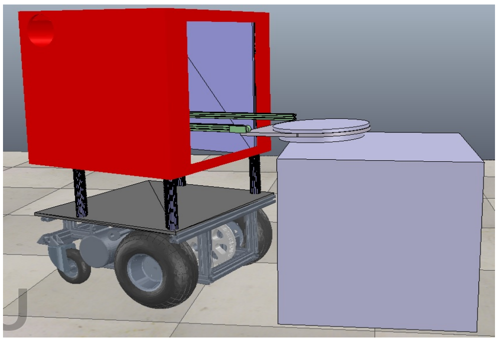

Figure 14: Hook mechanism

It is worth noting that, as recommended by the creators of CoppeliaSim, not all visual aspects were dynamically simulated, and were instead approximated by primitive shapes in a hidden dynamic model. Figure 15 shows this model, in which only components that interface with the tray are not approximated.

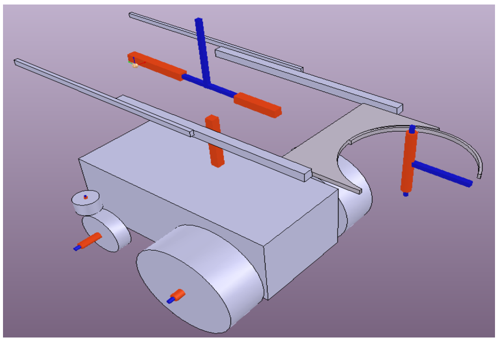

Figure 15: Dynamic model

The simulated Traybot can be seen performing a pick and place task under manual control **at this link**.

6 Evaluation-FEA report

6.1 Mobile base loadbearing

The 6063 aluminium frame of the mobile base is required to support the 80kg weight of the main body, and transmit this load to the wheels. Accordingly an FEA study was run, using an evenly distributed 784.5N force applied to the upper surfaces of the frame. Four fixed geometry load points were used in place of the wheels. Figure 16 shows the resulting deformation, exaggerated by a factor of 5000.

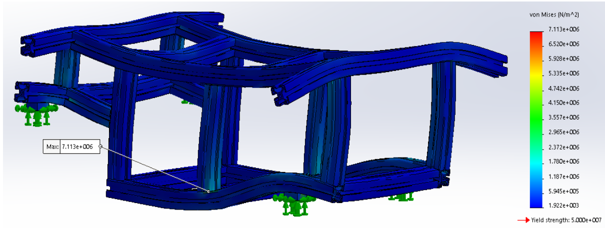

Figure 16: Loadbearing frame

The material yield strength of $5\text{x}10^7\text{N/m}^2$ is comfortably greater than the labelled point of maximum stress, which is $7.113\text{x}10^6\text{N/m}^2$, giving a minimum safety factor of 7.03. This indicates that the frame does not require reinforcement, and that it may even be possible to substitute an extrusion profile with a smaller cross sectional area.

However, these results should be interpreted with caution, as assumptions have been made. In reality the force produced by the main body will not always be evenly distributed, especially under acceleration or when a tray collection arm is extended. A more grievous assumption is that the framework is a solid body, in reality it is likely that the brackets used to connect sections of extrusion are much weaker than the extrusion itself.

6.2 Tray mechanism load bearing

When conducting a FEA of the tray mechanism some assumptions, much like the wheelbase had to be made. Firstly the tray mechanism in the FEA had to exist as a solid body, otherwise it would fail. This is not the case for a real life scenario as the telescopic element of the tray mechanism is naturally made up of multiple separate components. Four tests we conducted and the safety factor was the main point of investigation. The safety factor for this particular item can be relatively low, a safety factor of 1 would be acceptable because tray loads rarely vary in weight. Since food trays (carrying food) weigh only a few kilograms the FEA will match this quantity for the load force. This being said 4 FEA tests were ran for 1000N (101Kg approx), 100N (10Kg approx), 50N (5Kg approx) and 30N (3Kg approx). The results are shown in the table below.

Load force (N)	Min SF	Max SF
30	2.88	15
50	1.73	15
100	0.864	15
1000	0.0864	15

Figure 17: FEA safety factor for 1000 N

As you can see in Figure 17 the main impact is taken between the load and fixed linear rails. For this analysis this is acceptable but further real life scenarios should be tested. For example if someone chose to sit on the tray mechanism while it was ejected the main force from that load would be experienced through the bolts of the carriage plate which can be seen in figure 17. A possible problem which could arise if for example someone chose to sit on the tray mechanism and if it were to stay rigid then the robot could topple and land on the person. This could cause serious harm since the robot weighs approximately 100kg. One solution to this problem is for the bolts in the carriage plate to be made of a weaker material, therefore if an extremely heavy load were to be applied then it would simply break. This would protect the other components of the robot as it wouldn't topple over but also protect the people around it the robot. The weaker bolts in the carriage plate would have to be able to cope with the weight of a heavy tray but would break if the load exceeded 30+ kg for example.

7 Discussion

7.1 Design evolution

Initially the Traybot occupied a footprint of approximately $500mm \times 1000mm$. However, to improve the agility of the robot this was reduced to approximately $500mm \times 550mm$. If the robot size were to be increased then the Traybots ability to move through tight spaces is reduced. The Traybots height could be increased and therefore the number of trays and additional components could be added. Even so, this would increase the height of the robot centre of mass making it less stable, this issue would have to be investigated. If the Traybots functionality were be be increase, by adding heating or cooling components then the size for these components would need to be available. As you can see, the problem of size is one which needs to be solved if the Traybot is modified for additional components.

7.2 Tray mechanism

One component which has been mentioned previously is the addition of a breakaway mechanism for extreme loads on the tray mechanism. This mechanism would have to have a large lifetime which can handle cases for heavy trays but would be triggered in the case of a load above a maximum threshold. The mechanism would preferably be purely mechanical in the event of a cut from power. It would also be desirable if the mechanism could be reset instead of having to replace a part. Future research can be conducted to create a mechanism which fits this criteria.

7.3 Locomotion

Due to the 1:5 belt reduction from the DC motors to the driven wheels, the peak motor power of 800w is encountered at 7.48m/s. This is beyond the expected operational velocity of around 2m/s. However, at this velocity the available force of 213.85N is sufficient for overcoming a gradient of 11.82°, beyond the maximum expected gradient of 5° for wheelchair ramps. Calculations are given in appendix 9.3. These figures indicate that the chosen drive system exceeds expected operational demands, and the use of less capable motors could be acceptable.

7.4 Battery lifetime

The use of a single battery rated for 280.8Wh suggests that peak motor power could only be sustained for a maximum of 10.53 minutes. However, peak motor power would be rarely if ever required. If needed, the Traybots operational time could be extended with regenerative breaking. The mechanical design is capable of this without modification, but appropriate motor controllers, and battery changing circuitry would need to be sourced. Adding multiple small secondary batteries would also be possible, but would also require extra circuitry. Another approach would be to make a short operational time less problematic by devising a self changing system similar to the one used in [4].

This concept could also be developed further, wireless charging would be very much a possibility and would be extremely beneficial as it provides an additional level of autonomy as well as being far simpler than the robot attempting to plug itself into a charging socket. A wireless charging station can be placed in a permanent docking station. The Traybot would naturally know the location of said docking station. When the Traybot reaches low battery it will charge itself at the most convenient time. A secondary function could be if the Traybot is not required it can charge itself and therefore be fully charged when needed. The charging time of the battery we intend to use takes between 1 and 3 hours to charge. Regenerative breaking, as mentioned above, could provide a secondary mechanism for charging the Traybot. Due to the extra circuitry and controllers this may require more space and therefore the robot may need to be larger.

7.5 Maintenance

In the interest of the easy of maintenance the main components that would require attention are those belonging to the air filtration system. How is the air filter going to be changed if there is a UVC lamp in the way? A simple solution to this problem requires the whole system to sit within a 3 dimensional frame which can slide in and out of the tube where the air filtration system sits. Therefore, all electronics needed for the air filtration system will be disconnected during maintenance and when the air filter is removed it would be safe to do so. This also means that the UVC lamp or intake fans can easily be replaced if broken. Other components are expected to require less frequent maintenance, removal of the mobiles bases side covers allows periodic tensioning of the drive belts. Easy access through the top of the mobile base can be given by raising the upper body.

7.6 Control, sensing and interaction

For undertaking trails within a hospital, a physical prototype will require the development of a desktop or mobile application to allow tasks to be set by users. Additionally, non-users should be informed of the Traybots intentions when necessary by including a voice output, as found useful by the trialling of Helpmate [3]. Little can be said regarding control and sensing, as simulation was only conducted under manual control. However, this demonstrated the need for multiple views to obtain a precise approach for tray picking. Therefore it may be useful to mount some additional RGB cameras, and use brightly coloured trays to help visual servoing.

8 Conclusion

This paper has presented the motivation, design process, FEA analyses and simulation of an autonomous robot courier for use in hospital settings. CAD models have been produced to enable agile locomotion, airborne microbe sterilisation, and the reliable handling of containers. Initial results are encouraging, but the development of supporting software, and testing of a functional prototype in a safe environment is required. We anticipate that completing these real-world tasks would provide a better understanding of the Traybots feasibility and future potential for use in a hospital setting.

This testing will give us the ability to make critical decisions which would help improve the design and possibly simplify it. The software requires much needed attention, trial and error would not be acceptable in a hospital environment so the health and safety factor involving all systems is of great importance and should be considered as an individual project.

Overall, the main design of Traybot has improved significantly compared to that of the initial designs. Preliminary and critical reviews have made this possible, the feedback has been of great importance which has evaluated and acted upon where possible.

References

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9 Appendix

9.1 Github and Teams link

Teams link
Github link

9.2 Costings

The total cost of the components listed in tables 1 - 3 is £1,837.63, but numerous minor parts such as bolts, wires and connectors have not been accounted for. It is also expected that some listed components will require adapting or reworking. For these reasons, a 50% allowance has been added, bringing the total estimated cost of a functional prototype to £2,756.45.

Table 1: Mobile base cost breakdown

Mobile base components	Quantity	Unit Cost	Cost	Source
RS pro 30x30mm extrusion 1m	6	£21.34	£128.04	Vendor link
Pneumatic wheel	2	£9.11	£18.22	Vendor link
Castor wheel	2	£16.65	£33.30	Vendor link
DC motor	2	£46.99	£93.98	Vendor link
Encoders	2	£18.37	£36.74	Vendor link
Battery	1	£140.22	£140.22	Vendor link
DC motor controller	2	£19.99	£39.98	Vendor link
PLA filament 1kg	2	£18.50	£37.00	Vendor link
2mm Aluminium sheet 2 m^2	2	£71.28	£142.56	Vendor link
Custom steel plate estimate	1	£150.00	£150.00	
MG995 servo	1	£7.79	£7.79	Vendor link
Mild steel rod 2m 20mm	1	£29.86	£29.86	Vendor link
Mobile base total			£527.48	

Table 2: Main body cost breakdown

Main body components	Quantity	Unit Cost	Cost	Source
RS pro 30x30 extrusion/metre	10	£21.34	£213.4	Vendor link
2mm Aluminium sheet 2 m^2	3	£71.28	£213.84	Vendor link
Stepper drivers 10pcs	2	£7.56	£15.12	Vendor link
Air filter	1	£20	£20	
Fans	2	£10	£20	
Extrusion 20x20 per m	4	£7.54	£30.16	Vendor link
UVC lamp	1	£24.99	£24.99	Vendor link
MGN12 linear rail and block	8	£14.75	£118	Vendor link
Stepper motors	16	£10.47	£167.52	Vendor link
belts 5m	1	£4.18	£4.18	Vendor link
Belt tensioner	2	£8.66	£17.32	Vendor link
Carriage plates	8	£8.26	£66.08	Vendor link
Small steppers	4	£8.08	£32.32	Vendor link
Acrylic	1	£10	£10	Vendor link
Linear actuators	4	£49.25	£197	Vendor link
PLA filament kg	2	£18.50	£37.00	Vendor link
Main body total			£1,186.93	

Table 3: Sensing and control cost breakdown

Sensing and control components	Quantity	Unit Cost	Cost	Source
RGBD camera	1	£54	£54.00	Vendor link
Ultrasound sensor	8	£2	£16.00	Vendor link
Raspberry Pi 4	1	£53.22	£53.22	Vendor link
2D lidar	1	£95.80	£95.80	Vendor link
Sensing and control total			£123.22	

9.3 Locomotion calculations

Specifications for the mobile bases ZY1020 DC motors are listed **here**. The selected model is 800W, 36V, at 2750rpm with 2.78N/m torque. In the absence of more detailed specifications calculations are made for only these conditions. The selected motor pulleys have 20 teeth, and wheel shaft pulleys have 100 teeth, giving an output at the wheel of 550rpm and 13.9N/m. The driven wheel radius is 0.13m, giving a force per wheel of $13.9/0.13 = 106.92$N, and outer velocity of $550 \times 0.13 \times 2 \times \pi/60 = 7.487$m/s. Using the estimated total mass of 106.4Kg, and total force as 213.84N, acceleration $= 213.84/106.4 = 2.0097\text{m/s}^2$. This also allows calculation of the maximum slope which this velocity can be held over. $106.4\text{kg}\times 9.807\text{m/s}^2 \times \sin\theta = 213.85N$, $\sin\theta = 0.2049$, $\theta = 11.82°$.