MailBot: Evaluating the Impact of Human-Centred Robotics Design on Autonomous Mail Delivery Systems

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Abstract

MailBot is a human-centred autonomous vehicle that serves as an internal mail delivery system for the Electrical and Electronic Engineering department building at Imperial College London. MailBot is our proposed prototype solution to the challenges presented within the 'Final Mile' of delivery, the last stage of the delivery process of goods from a transportation hub to their final destination. This paper describes and justifies the final design decisions made based on the hypotheses that MailBot seeks to test, and presents the results from the subsequent human-robot interaction study. The study concludes that the quality of human interaction impacts people's willingness to use autonomous delivery robots and that demonstration of successful delivery will encourage its integration into a working environment.

1. Introduction

The parcel delivery service (excluding pickup, linehaul and sorting) around the world is estimated to cost approximately £55 billion annually, and almost 25% of the customers of this service are willing to pay more for faster delivery of their mail items [1], showing clear opportunity of improvement of this service.

The coming milestones for mail, postage and logistics will be realised through improvements to the cost and efficiency of the *Final Mile* of the delivery service, which is industrially recognised as the terminating problem step from depot to door which incurs the biggest reduction to profit and customer satisfaction [2]. Attempts to solve this include drone delivery - which is opposed by increasingly stringent air regulation and weight and weather limitations - and ground robots which currently struggle to accommodate multiple packages or endure today's large volumes of mail in their infancy [3, 4, 5].

Additionally, local post offices are decreasing in number, in contrast to the rapidly increasing volume of packages and urgency in which they are expected, creating large strains on existing logistics systems. Further agitated by the growth of e-commerce and its sporadic demands including 'Black Friday' and seasonal events, the infrastructure for a smart, re-configurable *Final Mile* service is becoming increasingly urgent.

The *Final Mile* problem critically relies on human interaction for both accepting and sending mail, coupled with understanding and answering user queries. Secondary interactions in collision avoidance or GPS tracking are also fundamental to the technologies' success. Here, we document MailBot: our group's proposed solution to the outlined problem. MailBot will first serve as Imperial's own internal mail delivery system taking packages across the campus, and then should advance to other workplaces as well as show its candidacy as a potential solution to the *Final Mile* problem.

Figure 1: MailBot testing on Imperial College campus.

2. Hypothesis

We propose two hypotheses to investigate, and ultimately assess, the acceptance of delivery drones by both end users and companies/organisations that might install the system for their employees/consumers.

1. A positive human interaction with an autonomous delivery robot, namely the physical design and tablet interface, will foster trust sufficient for the user to commit their package to the robot.
2. Demonstration of an autonomous delivery robot's usefulness over short distances will encourage its application within institutions and possible viability as a final mile solution.

While the outlined hypotheses mentions addressing a *Final Mile* solution, our MailBot is first and foremost an internal mail delivery system, so this is not the focus of our hypothesis evaluation.

3. Background and Preliminary Findings

In the last decade, next-day delivery has become a common and often-expected delivery option. Amazon is the largest advertiser of this service, offering *Prime Delivery* and even *Prime Now*, a 2-hour delivery service. An important part of this business model is the dependency on robots to automate the logistics of the picking and packing process in their fulfilment warehouses [6]. The obvious next step in the world of online shopping is to increase the efficiency of the delivery process. Amazon's drone delivery service [3] is not the only proposed solution. Large companies and organisations across the world are getting involved and providing automated ground-based services.

The Norwegian postal service has developed a locker on wheels, it moves at a walking pace of ≈4mph, which has been proposed as "a low-risk and environment friendly speed" [7]. As well as prioritising safety for the people around the robot and the bestowed packages, this slow speed adheres to human social expectations. Meeting subconscious movement expectations will portray the technology as trustworthy and facilitate enjoyable interaction [8]. Within movement and navigation some social conventions are clear, such as avoiding blocking other people's paths, while others are less tangible, such as motion in a predictable fashion and the effect that may have on the comfort of other users of that shared space.

The ability to interact with the user in a intuitive way is something that we believe requires more attention and thus, we have adopted successful properties from other products in the market while maintaining anthropomorphic features. Japanese company ZMP announced their take on the delivery bot in 2017, *CarriRo Deli* [9]. It features small eyes on the front LCD screen, displaying emotion to the user and providing a more comforting experience when interacting with the robot. Emotion builds a level of trust with the user and does not detach from face-to-face interaction in the same way that a phone app or text-based terminal would. Posard et al. showed that people feel a greater sense of trust exchanging a routine quantity such as a message or money with a foreign robot rather than a human [10]. This base level of computer trust is something that emotional interaction can strengthen. The *CarriRo Deli* also features interchangeable locker sizes. Within the roughly half meter cube shaped chassis you can insert one large locker, four medium or eight small compartments, incorporating the need for different parcel sizes as a must for general purpose delivery.

Autonomous parcel and grocery delivery service Starship technologies [5] have rolled out their six wheeled robot. While they have focused on the *Final Mile* of delivery, their use of a centralised docking point is of particular interest to us, allowing shorter and more regular rounds of delivery. This will reduce maintenance costs as when the battery's lifetime reduces there is less chance of a mid route break down.

Room service robots adopted by many hotel chains is a further example of a simplistic interface with automated delivery. *Savioke* [11], is a notable example that uses ROS [12], room service items are loaded from the front desk of the hotel and the robot navigates to the room to be unlocked as the customer opens their door. The robots are easily accessible and require very minimal interaction. Our robot however, requires a higher level of security due to the nature of its environment; the recipient of a package may not be the only person in a delivery location.

4. System Design

Inspired by existing autonomous delivery services as discussed in section 3, MailBot waits at a designated drop-off zone where users can approach it and bestow mail to its lockers. Drop-off would be in place of an organisation's current mail room or a central location such as a reception. The package sender selects the required package size from the interface and recipient's location, this generates a random PIN code for each mail item. When full or otherwise instructed, MailBot navigates to all delivery locations specified and alerts recipients to its presence in advance with an email containing the pin code, and upon arrival with a 'knock-knock' sound. It requests the recipient's PIN code to open the locker and, if successful, its contents can be retrieved. MailBot broadcasts the outcome of the delivery attempt to the involved parties and proceeds to the next one. When all deliveries are completed, MailBot returns to its drop-off zone to recharge and accept new mail.

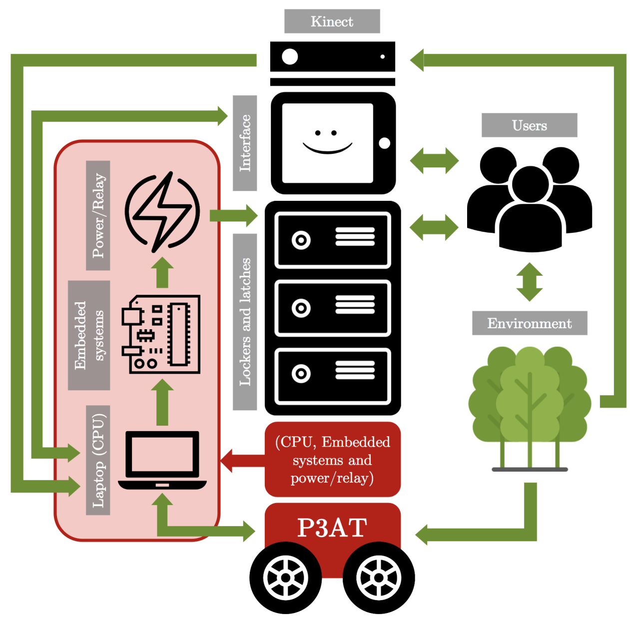

Figure 2: MailBot system and data flow diagram.

4.1. Hardware

MailBot's design takes inspiration from an Amazon locker, for functionality, and a post box to subliminally imply its purpose. Primary user interaction is through an onboard tablet which acts as a Bluetooth slave to the central ROS controller and allows users to book or receive deliveries, there are complimentary secondary interactions through email alerts and the robots physical motion. Navigation is facilitated by an RGBD camera interpreted by a central controlling computer which issues movement decisions to a drive unit and runs the ROS architecture. The ROS node network has been diagramatically represented in Figure 5.

Mailbot utilises a system of locking solenoid latches that work in conjunction with spring loaded doors to easily display to the user which locker has been allocated. The simplicity of this design ensures intuitive use and minimal maintenance. All latches are connected to a common embedded system which controls locker opening, the embedded system acts simply as a serial slave to the ROS node running locker operation.

The design requirements are: provide secure storage and transport of a large volume and variety of mail; provide mechanical, electrical and data interfaces for the drive unit, RGBD camera, latches, tablet and central computational controller; imply function through design and have an aesthetic appealing to users and prospective consumers.

4.1.1 General Construction and Decisions

Multiple drive units were made available, the P3-AT was chosen based on its wealth of library support and blank chassis on which lockers could easily be prototyped. Initial prototypes consisted of aluminium sheet curved into a cylinder to resemble a postbox but incurred too large a weight penalty, construction difficulty, and storage inefficiency to continue. Acrylic was also considered but its brittleness made it futile in supporting heavy packages and was likely to yield, or worse, shatter upon impact. MDF presented the clear choice as it exhibits appropriate flexibility and rigidity, is cost effective, and does not impose a significant weight penalty. MDF's significant drawback is poor weather resistance, but for the scope of this work it is superseded by the above attributes.

MailBot‘s design shown in Figure 3 is symmetric to enforce uniform weight distribution and hence uniform wheel friction, this is crucial to ensuring actuated steering is true to computer control. It also places its centroid in line with its centre of mass so any commands to rotate will produce a dependable change in orientation for both clockwise and counter clockwise. Initial builds had poor resistance to torsion and shearing forces, to overcome this shelf widths were staggered and increased by 1.5mm per level, this ensures constant outward pressure at all points on the robot to drastically improve rigidity and structural resilience to shaking and vibration.

A catastrophic and unrecoverable failure of the robot is poised by tipping. Crucially, the robots height is constrained to optimise moments of inertia about the drive spindles (y axis), and wheels (x axis) which acts to increase stability when travelling on uneven terrain, inclinations and during abrupt acceleration manoeuvres. For an unloaded vehicle, extremely pleasing tipping angles of $+/-23^o$ about its y axis, and $+/-25^o$ about its x axis were found. The height was also constrained to accommodate handicapped users, the wireless tablet is removable and mounted less than 1.2m above the ground so that it, along with the lockers, can be operated from a wheelchair. Additionally, the width of the robot is constrained to 530mm to allow travel through standard UK doorways with ample clearance of 96mm on either side.

The lockers mechanically interface with the P3-AT‘s chassis through a welded box steel frame for strength and build longevity; additional ballast was incorporated into the steel frame to lower the centre of gravity and hence increase the stable balance equilibrium to negate likelihood of toppling. Furthermore, the frame doubles as an electrical conductor to ground the lockers to the P3-AT so that if any electrical faults occur they are safely negated through the chassis.

4.1.2 Lockers and Latches

MailBot will be deployed in workplaces with varying size requirements, as such, the hardware design is completely modular to facilitate fast adaptation to environments and can be readily adjusted to meet developing needs. Moreover, there are no mechanical fastenings joining the modules or constituent panels, so alteration consists only of sliding one panel out for another without specialist tools or training. For each face, two struts form the main supports but double as a securing track to slide panels in and out of, the tracks hold the panels in place with compression from thread and locking nuts at the top, this is the only fastening necessary to remove for alterations. MailBot's modular design can accommodate 4 small letters (top) plus either 2 small parcels or 4 large letters or 16 small letters or combinations of these in any order.

Figure 3: Finished build of MailBot with coordinate axes.

The chosen sizes of lockers have been taken from the post office's standardised sizes so to comply with established dimensions for packages [13]. See Table 1.

Mail Type	Post Office Standard (mm)	Locker Size (mm)
Small letters	240 x 165 x 5	250 x 165 x 70
Large letters	353 x 250 x 25	500 x 372 x 70
Small Parcel	450 x 350 x 160	500 x 372 x 220

Table 1: Compatible Package Types and Dimensions

4.1.3 Electronics and Computing:

An Arduino was chosen as the embedded system to operate the latches due to its ease of development and serial support. The latch circuit shown in Figure 4 is additionally modular with solenoids being replaceable by connectors if modules are to be changed, preliminary tests blew fuses in the P3-AT so flyback diodes and decoupling capacitors were added in response.

A Linux-operated laptop is employed as a central computational unit to run the ROS architecture and several sensory slave nodes including a readily available Microsoft Kinect as an RGBD camera, Lenovo Tab 2 A10-70 tablet as an interface, and the P3-AT as the drive unit.

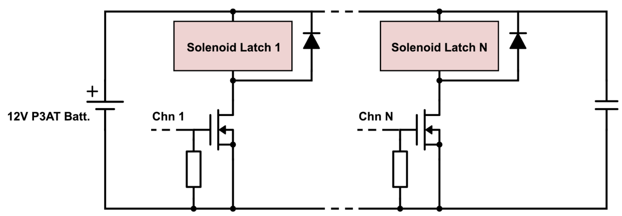

Figure 4: Schematic for Arduino-latch control circuit.

4.2. Mapping and Navigation

Mapping of the environment was created beforehand. For our purposes this is suitable, as mail delivery will only take place in known locations. We utilised a Real-Time Appearance-Based Mapping package (RTAB-Map) [14] that generates a database of images that enable MailBot to localise itself on the map based on a matching image ('loop closure') [15, 16]. Initial results were promising, however to generate a (global) map suitable for subsequent navigation, sensors needed to take distance measures at each location of the image to generate a 2D map. To do this we transformed the Kinect 1's depth information to simulated 'LaserScan' information.

For localisation, the ROS Navigation Stack was used together with Adaptive Monte-Carlo Localisation (AMCL) and RTAB-Map localisation systems. The RTAB-Map node published a global map and applies 'loop-closure' to transform MailBot's current location to the appropriate location in this map. This 2D global map is additionally suitable for AMCL to use laser based sensors to localise with. Here we continued using the 'LaserScan' converted depth images to simulate laser data. A Dynamic Window Approach (DWA) based planner was used for smaller local paths in this global map [17, 18, 19]. Local path planning was using the highly directional 'LaserScan' converted depth images. We split the information into both short-range (0.15-3.5m) and long-range (3.6-12m) bands to manipulate the DWA planning algorithm. This accounts dynamic obstacles in the obstacle map (costmap) better. The obstacle detection algorithm is only able to remove potential obstacles when sensor data is received beyond the original obstacle (raytracing); this segmentation of the sensor data increases the likelihood that this occurs. Furthermore, we utilised a long forward-simulation of trajectories, this promoted fewer changes in the path direction, making paths smoother. Recovery behaviours were low angular velocity rotations: this made the robot seem less disruptive and allows more images to be taken per complete rotation, improving the likelihood of finding a match suitable for loop closure with the RTAB-Map Localisation system. Delivery routes are solved to provide an efficient global map route to reduce the delivery cycle duration and seem intelligent when observed. The system must also make sure that the it handles any errors or unexpected behaviours that occur.

4.2.1 Mapping Issues and Decisions

Originally a Kinect 2 was used, however the serial bandwidth of the laptop could not handle the large data volume, preventing the opening of serial ports to other hardware, such as the Arduino. Technically, for mapping purposes the default 30fps of images sent to the machine was much larger than necessary for generating database image frames; although it is possible to only process certain frames and even downsample frame resolution for subsequent processing, being unable to communicate with other hardware forced us to move to the Kinect 1. Sonar data was originally converted to the 'LaserScan' type data to give us almost 360 coverage of the robot's surroundings, but test maps using this data were not promising, likely due to the strong directionality, large standard deviations and noise of the sonar system's readings. While RTAB-Mapping is effective in establishing a map based on images and odometry data, the algorithm compares SIFT features of the image database to establish 'loop closure'. The walls and the floor could easily cause false positives, hence we ignored the bottom half of the image data to help remove features on the floor that confused localisation [20]. To improve further, the hardware was redesigned for the Kinect camera to be mounted as high off the floor as possible to give better angle for image collection.

4.2.2 Navigation Issues and Decisions

Issues with navigation stemmed from our use of depth images converted to 'LaserScan' data. Inherent limitations were the effective depth range - up to 4m [21] - and the highly directional nature of the information (horizontal field of view 58.5° [21]), always in the direction the camera was facing. We found that obstacles were easily marked onto the costmap but were not as easily removed by raytracing, we thereby needed to employ specific settings to ensure that dynamic obstacles, such as passerby's, were effectively removed from the costmap during navigation. A laser scanner likely would have made removal of dynamic obstacles easier and aided localisation, however the laser scanner we procured at late stage testing was regrettably defective.

4.2.3 Route Planning Issues and Decisions

The route planning system must take in a list of delivery locations and some information about travelling between these locations, then produce an efficient series of goals for the navigation stack to travel to. It must also act as a queue, ensuring new locations are only provided when the interface has completed its loading or delivery script for the current location. Few ROS packages exist to solve this problem and those that could be found were part of bespoke packages specific to that robot design. To ensure the system could be integrated to our overall design and easily customised, route planning was built upon a simple python "Travelling Salesman Problem" (TSP) solver [22]. Many libraries, such as the Concorde solver, exist to solve this problem to varying degrees of optimal efficacy.

The chosen library is sub-optimal, but for the limited number of possible delivery locations at one time, it has negligible difference from more complex solvers and provided an interface better suited to the customisation required. Some solvers require path costs to be input as co-ordinates to be converted to distances, often in a specific TSP format. They also solve for all possible locations. The chosen solver requires only a matrix of costs between each location. The routes to visit are only a subset of all possible locations, so our global cost matrix is reduced to only those locations then input. Because the cost matrix is in arbitrary units, we can also choose whether our costs are distance, time or any function of factors.

The final design is fully integrated, using dummy cost matrix values. Once it receives a list of locations from the interface it produces an intelligent order to visit them and passes the first goal to the navigation stack using a ROS action. When it receives a result from this action, it notifies the interface that the robot is at that location, allowing it to run the corresponding delivery script. When the interface is done at that location either by a successful or failed delivery, it notifies the queue and the next goal is set.

4.3. Interface

4.3.1 Design Alternatives

The primary requirements of the user interface were that it must: look inviting to potential users, provide a concise user experience for the sake of efficiency and be intuitive and easy to use.

Using a remote control to navigate through a series of screens [23] and interact with MailBot was deemed less intuitive than a tablet. People are quicker and more used to providing input via a tablet/smartphone interface. Dialogue-based interaction was also considered, however, this mode of interaction is error-prone and more likely to cause frustration than manual entry of information. The user interface chosen was an application developed using Android Studio. It has the same design and activity layout as outlined in the Supplementary Figures of our Design Report [24]. The application-based user interface presented itself as the most inviting and intuitive option after alternatives were considered.

Originally, communication was coordinated between the serial ports of the tablet and the computer but this would have added external wiring, which some users might have found aesthetically off-putting. Moreover, given the number of devices communicating through the serial port, the system may have acted unreliably if timings ever misaligned. The final system contained Bluetooth communication between the two devices, exploiting the network illustrated in Figure 5. Bluetooth has the additional benefit of making it possible to detach the interface for ease of use, if necessary.

4.3.2 Interface Functionality

The interface treats each locker as a distinct object and all associated data, including the PIN code, is created and stored locally. The tablet and computer are constantly communicating over Bluetooth to share data and to provide event cues, such as destination arrival or when to open the locker.

When MailBot arrives at a delivery location, the computer tells the interface which location it has arrived at and this information is used to retrieve the locker details from the database. A 'knock-knock' sound is played through the tablet to notify the recipient of its presence, who is then prompted to confirm that they are expecting mail. If they are, they can provide the PIN code to access the locker. MailBot updates the senders and recipients as to the outcome of the delivery attempt.

5. Experimental Procedure

To assess the hypotheses, MailBot has been taken to the public for demonstration, see Figure 1. Using a simple demo of the system‘s operation, where MailBot navigates between two points in a public place allows users to experience the interface and form opinions about how the robot works and other factors outlined in the hypotheses. Upon completing the demo, users were asked to fill out a short survey [25] with questions targeting both hypotheses.

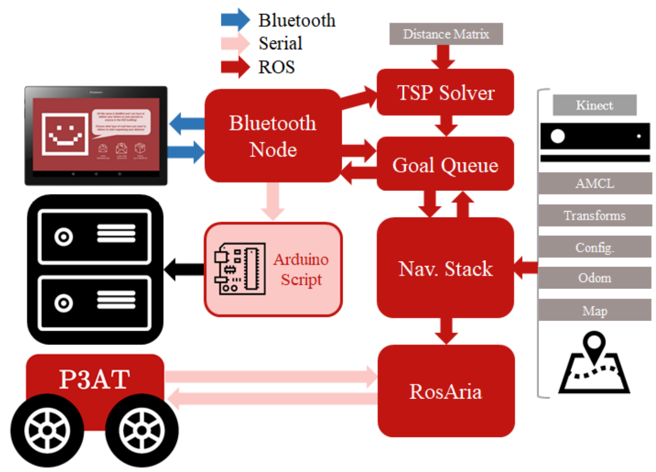

Figure 5: Diagram showing connections between ROS nodes and other systems.

Questions such as "Which aspects of MailBot invoke trust in its use?" allow users to select specific aspects of the design, such as the *physical design*, *tablet interface* and *MailBot's motion*, that provide them most confidence in the system.

The distributions of three key parameters were determined through the survey: Quality of Human Interaction (Q), Level of Trust for MailBot (T) and Usefulness of MailBot (U). These were calculated by averaging the distributions of the survey questions most related to a specific parameter. The Q, T and U-distributions allowed us to conclude whether the results supported our hypotheses. The indices are scaled such that 1 refers to a low standard and 5 refers to a high standard for the index.

The Q-index is quantified by questions that assess the impressions made by the design and how intuitive the overall system is to use. The T-index is calculated using responses that gauge user comfort with MailBot, such as whether or not users agree that they "feel comfortable approaching the robot". A conclusion for hypothesis 1 is determined using the quality of human interaction and perceived trust indices.

The U-index of MailBot will be assessed in questions that address both efficiency and convenience. To properly compare these factors, questions were asked about both current mail systems in a users place of work (if applicable) and how they perceived MailBot's efficiency and convenience. This includes questions such as "How do you perceive MailBot's usefulness in the workplace?" and an agree/disagree response of "Using MailBot would make internal mail delivery more efficient". A conclusion for hypothesis 2 is based on the response to the perceived usefulness index.

6. Results and Discussion

The performance of MailBot was assessed by the results of the survey obtained following public demonstrations. The sample size (n) for the survey results was 32 and the participants answered 14 questions [25]. The distributions of the three key indices were calculated using the results and are illustrated in Figure 6 and Figure 7.

Other indicative results came from the question of "Which aspects of MailBot invoke trust in its use?" and general feedback.

These responses suggested that the most convincing aspects of the MailBot were: its similarity to existing systems (voted by 81.3%) and its email service (voted by 59.4%), whereas its least convincing feature was its motion. Only 6.3% of those who participated in the survey were faithful in MailBots ability to move. This was echoed in the general feedback where 15.6% of the responses commented on the state of the motion in this MailBot prototype.

6.1. Hypothesis Testing

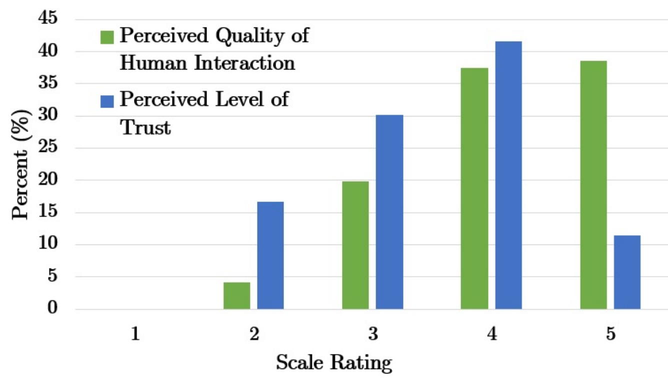

Figure 6: Quality and Trust distributions.

Parameter	Value
$\mathbb{E}\{Q\}$	4.11
$\mathbb{E}\{T\}$	3.48
t_{exp}	1.2690
Pooled Variance	0.7767
Degrees of Freedom	8
Confidence Interval	75.99%

Table 2: Table containing parameters for the Student's t-test and the resultant confidence interval.

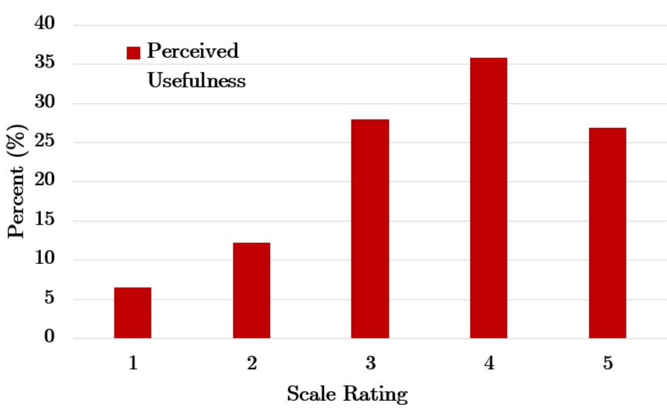

Figure 7: Usefulness distribution.

Hypothesis 1 was assessed by comparing the similarity between the Q-distribution and the T-distribution, shown in Figure 6. A notable similarity is indicative of a correlation between quality of human interaction and perceived trust. This correlation would imply that a positive human interaction fosters trust in the use of MailBot. A two-tailed statistical Student's t-test yielded a 75.99% confidence interval for the similarity between the two distributions, using the t-test parameters shown in Table 2. This value indicates that there is at least a positive, if not strongly positive, correlation between the two indices in this experiment which supports hypothesis 1.

Hypothesis 2 was assessed using the U-distribution, depicted in Figure 7. More than 60% of those who observed MailBot agreed that it would be a useful robotics system to have available in a workplace. The majority of the remainder were conflicted, citing the existence of mail delivery services as a deterrent to implementing a new one. Despite this, more than 40% of those surveyed confirmed [25] that delivery services in professional environments tend to be poor and 55% agreed that MailBot would make internal mail delivery services more efficient. This holds true at Imperial College, which was the focus of this study.

6.2. Hardware

Confidence in our design was proven by the public majority finding MailBot's function obvious, and further augmented by a mean approachability score of 75.6%. 37.5% of users recorded physical design as being an obvious contributor to initial trust in the robot.

There were however some negative opinions of MailBot's stability when moving. 15.6% of responses mentioned the movement as being "unstable" or having a "wobble". This issue is mostly due to limitations set by the P3-AT's wheels. The solid rounded rubber tyres grip to surfaces as MailBot rotates, causing jolted or wobbly movements.

6.3. Mapping and Navigation

The visual localisation approach has proved to be viable for indoor environments. It would be interesting to see its performance for cross-building deliveries where it may need to navigate outdoors, thereby necessitating an outdoor map.

Local path planning purely with the RGBD Kinect sensors has been surprisingly practical. Existing issues arise from dynamic obstacles not being removed from the costmap. Our findings suggest that reducing the range at which to add obstacles to the costmap to 3m, while maintaining a large distance capable of remove obstacles (i.e. 10m), improves this sufficiently for our purposes.

Performance of the route solving algorithm and integration with the interface is acceptable. There is no significant delay between communication, and chosen paths are intelligent and efficient.

In one case, where the navigation stack fails to find a route, there is some undesirable behaviour as the navigation stack still returns a result and this is interpreted as arriving at a location by the queue, triggering the interface script. This could easily be fixed by parsing the result and setting some recovery behaviour, preventing the negative perception this unusual behaviour may incite in people who observe it.

6.4. Interface

The expected value for the perceived quality of human interaction index was 4.11, seen in Table 2. This score suggests that users had a positive human interaction with MailBot. The user interface is the main source of interaction with the system, meaning that it strongly influences the Q-index. The positive performance in this metric is satisfactory for this design, but a detailed inspection of the results highlighted aspects of the interface that are worth improving.

More than 65% of those surveyed felt comfortable around MailBot, 46.9% claimed that the tablet interface contributed to their sense of trust in and 59.4% claimed this about the email service. This implies that the user interface does moderately succeed in inviting in potential users. However, a non-trivial amount of people did not find MailBot as inviting as expected, this result requires testing but a potential means of identifying the main points of attraction in the interface is real-time eye gaze tracking.

Results showed that approximately 56% of the sample population believed that using MailBot would make their internal mail delivery service more efficient. This suggests that this same percentage were convinced that MailBot itself provided an efficient service, which can be attributed to its concise user experience. The majority of those who were not convinced neither agreed nor disagreed that MailBot would make the internal mail service more efficient. The expected value for *perceived usefulness* index was 3.93 seen in Table 2. Its value is much closer to 4 than to 3, suggesting that the concept for MailBot is generally viewed as useful. An efficient approach to internal mail delivery services contributes to this opinion. Any current lack of faith is likely to come from the overall prototype feel and performance of MailBot, but can be improved in subsequent iterations of the system.

Over 65% of participants thought that the application was intuitive and 31% neither agreed nor disagreed however, a non-trivial amount of users were still not convinced by the ease of use of the interface. This is not completely surprising. The interface lacks a help screen for first-time users and so, for some, requires a demonstration or explanation as to the workings of the system.

7. Future Work

7.1. Hardware

Based on experimental results, subsequent designs should be constructed from sheet steel using more developed fabrication techniques such as folding, stamping and spot welding. This will create a light but robust housing taking the same shape as the current design and is likely to foster greater trust in consumers correlated to increased value of items entrusted for delivery while also permitting weatherproofing. Adding suspension in conjunction with all-terrain wheels would help alleviate user distrust due to shaking and mechanical resonance when moving. Several technological upgrades are necessary for campus-wide movement such as interfacing with lifts, doors and charging docks. There are also other enhancements such as biometric identifiers and GPS tracking which would be relatively straightforward to install and have promising return in user satisfaction and scalable logistics. Should this robot be developed as a solution to the *Final Mile* problem we would need to see drastic improvements to the robot's battery capacity, RGBD sensor number and resolution, autonomous navigation, and sophisticated collision avoidance and planning. Aside, a novel technology which hasn't been explored yet commercially is automated transportation of packages requiring a controlled environment, stipulated most likely by temperature and humidity; creating a locker module with environmental control could be especially useful at Imperial College for transport of chemical, biological and perishable samples.

7.2. Navigation

7.2.1 Mapping and Localisation

Mapping & Localisation were greatly improved through RTAB-Map, however, the low quality 2D maps highlighted the poor quality of our sensor data. Future work should involve improving the sensory inputs. Possible solutions may be: sonar normalisation and angular upsampling or utilising a laser scanner.

Normalisation might involve some form of redundancy style calibration with the Kinect depth information, we can thereby leverage off the accuracy of the Kinect to improve sonar accuracy. Additionally, this could be used to forcibly reduce the variation observed in sonar readings to match that of the Kinect. Currently, the directional nature of the sonar means that distance data is increasingly spaced out in angular space the further away objects are, a way to upsample the angular positional information would likely improve map quality. The main benefit of this option is that no additional hardware is required. The main disadvantage ins that the sonar is audibly noisy, and so it might be irritating to users in certain indoor environments. The alternative option of using a laser scanner would be the superior sensory option due to its larger field of view and effective range. The main disadvantage would be the added cost to a final system.

Visualising more obstacles in the environment and clearing of obstacles in the costmap, such as increasing the field of view and increasing the effective range respectively, are enhancements that would improve navigation further. These directly relate to the aforementioned improvements to Mapping and Localisation.

7.2.2 Route Planning

Some simple fixes would be included in future work. These include improving the error handling of the system to provide better recovery behaviour in case of errors propagated by the navigation stack and ensuring the depot location is included the costs for routes correctly.

A larger avenue of future work is performing experiments on how updating the cost matrix dynamically and the chosen factors used to model this cost might affect the efficiency and perception of the robot. Time taken to travel between locations may be a better function than Euclidean distance as it accounts for some level of traffic, handled by the local movement planner. The robot can easily store updated cost matrices, allowing it to improve its planning over time by recording the effect of certain factors. The possibilities for modelling this cost are great, from understanding simple distance to accounting for typical traffic routes based on the college lecture timetable.

7.3. Interface

7.3.1 Help Screen

Future iterations of the interface would benefit from a help screen, which would be accessible from the home page of the interface. This area would present diagrams and written instructions, and possibly verbal instructions, explaining how MailBot works in detail. The content would serve to reduce the chance of confusion for people who are less familiar with tablet-based interfaces. This should make use of the tablet more intuitive over time.

7.3.2 Multiple Security Levels

Additionally, to increase user trust, MailBot should provide the option to add multiple levels of security to a locker. Possible options for this would include face recognition and voice recognition. The face recognition could compare a recipient's face to a pre-existing database of faces to ensure that the mail item has been delivered to the correct person. The voice recognition could consist of a randomly generated verbal phrase.

7.3.3 Eye Gaze Tracking

The focus of a user's eye gaze can be a useful indicator of their attentiveness and engagement with an interface [26] and serve to produce invaluable human-robot interaction metrics. Future iterations of MailBot interface should include real-time gaze estimation software with the tablet's in-built camera and use the results to quantify how user engagement changes throughout their interaction with the interface. This would allow further changes to be made that improve the quality of human interaction.

8. Conclusion

An external evaluation of our final product was achieved by displaying MailBot in the main entrance of Imperial, where users could see and test out its functionality. According to surveys filled out by the public, MailBot successfully proved our two hypotheses: MailBot's perceived trustworthiness and usefulness. This is further elaborated in subsection 6.1

While we do not claim MailBot is a final solution, and suggest further improvements in **section 7**, we have successfully built a prototype that exceeds the expectations of a basic internal mail delivery system by creating a comfortable and familiar experience for the users by highlighting human-centred designed features. In a sector where around 425 000 people are employed (as delivery drivers and couriers) [27]. with a median salary of £15 000, MailBot presents a realistic alternative with a great profit opportunity, which will become increasingly more widely accepted and trusted as drone and robot based delivery systems become normalised.

As further studies are conducted in the field of human-centred robotics, and more companies test out robotics-based solutions to the challenges presented in the *Final Mile* of delivery, it will become clearer that systems such as MailBot could reform the efficiency of our current mail service.

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