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Understanding Human-Robotic Lawnmowers Interaction in Different Contexts

An exploratory study to understand and improve human perception of autonomous mobile robots

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Swedish title: Förstå interaktionen mellan människor och robotgräsklippare i olika sammanhang
Swedish subtitle: En explorativ studie för att förstå och förbättra människans uppfattning av autonoma mobila robotar

Abstract

Human-Robot Interaction (HRI) covers studies on interactions with robots and how to improve them. This project focuses on the interaction between humans and autonomous mobile robots (AMRs), such as autonomous lawnmowers, sharing the same physical space. It is established that trust is crucial to enhance human-robot interaction, and intent communication is explored as a way to engender trust. We explore this through two modalities — movement and light. The motivation to choose these stems from the fact that they are simple and have a low knowledge threshold. We developed unique movement cues coupled with light patterns that convey two intents: yielding (backing off) and making way (indicating a human to move) for 4 scenarios. We conducted an online video study to evaluate the legibility and effectiveness of the developed behaviours and ran a qualitative analysis of the open-ended responses generated. We also collected quantitative data through a 5-point Likert scale that assesses the safety perception and trustworthiness of the mower. We conclude that safety perception and trustworthiness of a robot is closely tied to whether the robot shows social behaviours. Apart from this, we also developed a repository of interaction behaviours that are suitable for the 4 scenarios we explored, this lays a foundation for future work where other scenarios (group dynamics, varying population density, etc.) can be explored and behaviours added to the repository.

Keywords

Human-Robot Interaction, Social Robotics, Multi-modal Human-Robot Interaction, Intent Communication, Interaction Design.

Sammanfattning

Interaktion mellan människa och robot (HRI) omfattar studier om interaktioner med robotar och hur dessa kan förbättras. Detta projekt fokuserar på interaktionen mellan människor och autonoma mobila robotar (AMR), såsom autonoma gräsklippare, som delar samma utrymme. Det är fastställt att förtroende är avgörande för att förbättra interaktionen mellan människa och robot, och avsiktlig kommunikation utforskas som ett sätt att skapa förtroende. Vi undersöker detta genom två modaliteter — rörelse och ljus. Motiveringen till att välja dessa kommer från faktumet att de är enkla och har en låg kunskapströskel. Vi utvecklade unika rörelsesignaleringar kombinerade med ljusmönster som förmedlar två avsikter: att ge efter (backa) och att göra plats (indikera att en människa ska flytta sig) för fyra olika scenarier. Vi genomförde en online videostudie för att utvärdera läsbarheten och effektiviteten av de utvecklade beteendena och genomförde en kvalitativ analys av de öppna svaren som genererades. Vi samlade också in kvantitativ data genom en 5-gradig Likertskala som bedömer uppfattningen av säkerhet och tillförlitlighet hos gräsklipparen. Vi drar slutsatsen att uppfattningen av säkerhet och tillförlitlighet hos en robot är nära kopplad till om roboten visar sociala beteenden. Förutom detta utvecklade vi också ett arkiv av interaktionsbeteenden som är lämpliga för de fyra scenarier vi utforskade, vilket lägger grunden för framtida arbete där andra scenarier (gruppdynamik, varierande befolkningstäthet, etc.) kan utforskas och beteenden läggas till i arkivet.

Nyckelord

Mänsklig-Robot-Interaktion, Social Robotik, Multimodal Mänsklig-Robot-Interaktion, Kommunikation av Avsikt, Interaktionsdesign.

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Stockholm, June 2024
Shashank S. Shirol

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List of acronyms and abbreviations

AFF	Autonomous free-flyer
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
AV	Autonomous Vehicle
DRL	Deep Reinforcement learning
HCI	Human-Computer Interaction
HRI	Human-Robot Interaction
NLP	Natural Language Processing
ROS	Robot Operating System
SDG	Sustainable Development Goal
TiA	Trust in Automation
UN	United Nations

Chapter 1

Introduction

Human-Robot Interaction (HRI) [1] comprises studies, as the name suggests, of human interaction with robots. The field is multidisciplinary, with contributions from Human-Computer Interaction (HCI), Artificial Intelligence (AI), Natural Language Processing (NLP), design, and psychology; with research spanning multiple domains, sometimes overlapping domains.

Previous research in HRI [2, 3, 4] establishes that trust is crucial to enhancing human interaction with robots, and “Safety” is critical to ensure trust building. This is at the core of what we aim to achieve in the current study. Establishing safety in a Human-Robot Interaction can vary a lot — from a philosophical approach of assuming robots are individuals with moral agency to more practical approaches of creating safety zones when interacting with robots. In this study, we focus on intent communication as a mode to improve safety perception and trust building.

Furthermore, we focus on a special class of robots, called Autonomous Mobile Robots (AMRs)[5], which has seen a steady growth over the past decade in the form of robotic vacuum cleaners and lawnmowers. While the development in this space has been focused on improving the efficiency and longevity of the machines, little work has been put into making them “social”. Apart from an on-board collision detection mechanism, there isn’t much to make them socially aware of their surroundings and act accordingly. This is a real threat for owners with pets, in the case of a vacuum cleaner, and, for humans coexisting, in the case of semi-large lawnmowers. In this project, we have a closer look at autonomous lawnmowers and augment them both, structurally and behaviourally, to assess how these augmentations affect human perception of the robots. The idea is, if these robots exhibit social behaviours that indicate situational awareness (by communicating intent), humans would feel safe, and thus improve human perception. We test this by developing behaviours for the robot that are suitable for specific scenarios and conducting a user study to assess how they are perceived. 1.1 shows an overview of the different components included in this study.

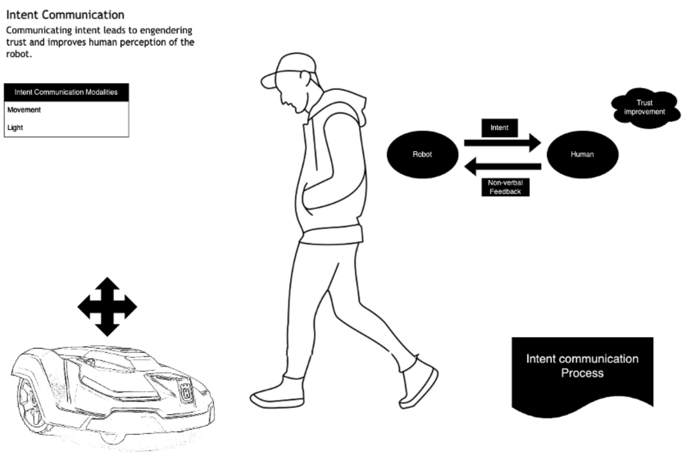


Figure 1.1: An overview of the different components of this project

1.1 Problem

Autonomous mobile robots are increasingly becoming a part of the workforce and other operations. For an amicable coexistence between the robots and humans that share space, further deliberation and insights into the human-robot relationship is warranted. There is an urgent need to study how human perception of these mobile robots can be improved. Trust is a crucial parameter [4, 6] when it comes to refining human perception of robots, and previous works have explored intent communication as a medium to engender trust [7, 2]. In other words, when a person can predict robot intentions, they feel more relaxed around the robot. There are several ways to communicate intent, making use of various modalities to do so. Recent advancements in non-conventional interfaces [8] for interaction present an interesting avenue for research, but when it comes to service robots, like an autonomous lawnmower in our case, we cannot rely on complex technologies to convey intentions as most of these usually have steep knowledge threshold. The fact that these service robots operate in public spaces further complicates this problem as they would encounter people with varying levels of knowledge.

Thus, we have to leverage modalities that have a low threshold for knowledge. Two modalities we decided to work upon, therefore, were movement and light. Lights are simple, and can be used in expressive contexts that can successfully highlight the robot's internal states and other intentions. Movement is as elementary as it gets, when it comes to communicating motion intent, people begin reading movement as infants [9] and build upon the mental models throughout their life, constantly assessing and making minute decisions based on movements around them. Therefore, combining these two modalities offers a unique opportunity to explore intent communication.

1.1.1 Original problem and definition

This project explores how the behaviours of robotics lawnmowers in public spaces, particularly in parks and golf courses, are perceived by pedestrians and other humans in the scene. This study aims to inform what behaviours within the robot movement or external signalling, such as light, could improve the interaction, how safe individuals feel around robotic lawnmowers, and how the robot's mechanical efficiency and effectiveness are perceived based on their operational behaviours.

This leads us to the following research question and hypothesis:

RQ: How will the behaviour of robotics lawnmowers, acting upon the multimodal input received from the environment, be perceived by pedestrians and other humans in the scene in terms of Trust and Safety?

H: Successful communication of intent by a robot could positively influence the perception of trust and safety toward that robot.

1.2 Purpose

The research question examines the impact of augmenting an autonomous robotic lawnmower with behaviours that would make the robot more socially "aware," we explore two different modalities to achieve this – movement and expressive lights. If the special behaviours we design using movement and expressive lights are successful in communicating robotic motion intent, this would take us a step further in creating a future where robots and humans can coexist in a space. This work would also help understand the dynamics of a dyadic human-robot relationship.

1.3 Goals

The goal of this project is to develop interaction behaviours for autonomous mobile robots, that operate at below standard eye-levels, such that they effectively communicate robotic motion intent while engendering trust within humans that coexist in its physical space. This has been divided into the following two sub-goals:

1. **Subgoal 1**
   Develop viable interactions that are effective, cost-efficient, and make the robot "socially" intelligent.

2. **Subgoal 2**
   Explore patterns in movement-based and light-based communication to apply to autonomous mobile robots and to translate findings from other domains and test them here to verify cross-domain applicability.

One of the deliverables of this project is a repository of interaction behaviours that are designed for mobile service robots, particularly, to communicate intent. These interactions explore general scenarios that AMRs may encounter in their day-to-day operation. We explore this space through an autonomous lawnmower that operates in public spaces and encounters humans in various ways. Furthermore, we use statistical analysis to assess the impact of these intent communicating behaviours on safety perception and trustworthiness.

1.4 Research Methodology

Since the primary objective of this project is to develop interaction behaviours using movement and light as modalities to effectively communicate intent, we begin with an elaborate pre-study that explores communicative movement [10, 11, 12] and expressive lights [13] and how these have been used in various contexts. We also looked at parameters that define a successful human-robot interaction, like human-robot proxemics [14]. We then establish scenarios we would like to explore and where it might be relevant to use movement and light as communication modalities. Thereafter, we specify the various intents we wish to communicate through developed interaction behaviours. These are chosen based on relevancy and operational importance for the robot we are working with.

After the theoretical groundwork, we set up an online video-study that tests these behaviours and interactions. We employ standardized questions pertaining to safety and trust that are derived from Trust in Automation (TiA) [15] questionnaire and also some additional questions based on relevance. We also conduct a qualitative online video study where participants watch videos of the interaction behaviours, and we evaluate the legibility and the effectiveness of conveying the intent of the behaviours.

At large, we conduct exploratory research that aims to assess the viability of movement and light-based motion intent communication models in AMRs.

1.5 Delimitations

Studying how to make service robots social is a multi-faceted challenge that involves human-robot interaction in multiple contexts, such as in a group, individually, pertaining to different demographics, etc. Owing to the limited scope of this project, we restrict our study to individual (one-on-one) human-robot interactions, leaving the study of group dynamics for future works and extensions of this project. We also work exclusively with movement and light as modalities for intent communication; although there are various modalities that warrant exploration, we cite the length of this project as a limiting factor and the fact that exploring these different modalities would require significant structural changes to the robot which, in itself, impacts human perception [16]. Future works that extend this project could test visual, haptic, and sonic modalities to further explore how these modalities impact intent communication efforts.

1.6 Structure of the thesis

Chapter 2 presents relevant background information about social robotics and how it is playing a key role in ensuring a future of human-robot coexistence. Chapter 3 articulates the design and ideation process. Chapter 4 presents the methodology and methods used to solve the problem of engendering trust and improving human perception, and also covers details about the experimental setup and the questionnaire curated for testing the developed behaviours. Chapter 5 delves into our findings and our analyses of the data generated from the experiment. Chapter 6 describes our results and conclusive information derived from it. We also highlight areas that could be looked into further by future works that would further help bridge the gap between human-robot coexistence.

Chapter 2

Background

Simply put, HRI, as a field of study, aims to study how to enhance user-interactions with robots. It is a multidisciplinary field that draws upon knowledge from robotics, computer science, psychology, cognitive science, and social sciences, among others, to design, implement, and evaluate robots capable of interacting with humans in ways that are safe, effective, and meaningful. One aspect of making user-interactions more successful is by making users feel comfortable and relaxed around the robots. Research [17, 18, 19, 20, 21] in psychology and social sciences reveals that engendering trust is a known way to enhance interactions with other humans, and studies in HRI [7, 6, 3] corroborate this claim regarding human-robot interaction. In this chapter, we will explore trust and safety perception of robots and also the role of attention and expressiveness [22] in improving human perception of robots. We will also discuss how intent communication serves as a conduit for trust building in human-robot interactions. The Related work section of this chapter explores similar work conducted in other domains like Autonomous Vehicles (AVs) [23], Autonomous free-flyers (AFFs) [24], and how our understanding of Human-Robot proxemics [14] helps us to build reasonable interactions to communicate motion intent. We will also explore the existing use of multimodal interfaces [8] for intent communication in robotics for the sake of completeness and to present the reader with a holistic idea of where the current study could be placed in the literature.

2.1 Trust and Safety in HRI

When robots are placed in a collaborative human-machine teams and are capable of making independent goal-oriented decisions, it affects the performance of the team such that it is considered a shift from traditional human-machine settings where humans would operate the robots. Communicating intent, in this scenario, is critical since these independent decisions are subjected to human trust and existing mental models. Past research in this area [7] finds that mounting a display on the robot and providing contextual information through the display maintains a human's knowledge level of the machine, which proves helpful and reduces the likelihood of humans misinterpreting the machine's actions. This is especially important since human perception of the machine plays an important role in trust degradation and unnecessary interventions, leading to abandonment of the machine. Further research [6] in the same domain explores the role of trust and safety perception in the context of AMR, particularly industrial AMRs. They determine the need for improving safety perception and trust within humans, coexisting in the same space as autonomous robots. They look at existing evaluation methods and their effectiveness. Other research [2] argues the importance of trust in HRI by citing the nature of humans toward strangers and how this effect is accentuated with robots, where there is an even higher level of unknown. They gather data that identifies the importance of trust in HRI.

2.2 Attention and Expressiveness in HRI

One can usually predict the role of attention and expressiveness in human-robot interaction solely based on lived experiences and other interactions they might have had with the world. Past research by A. Bruce et al. [22] in this area aimed at evaluating human responses to robots based on their expressive capabilities and attention behaviours. The study investigated how the ability of a robot to convey expressions and demonstrate attention, by turning toward the person, impacts people's willingness to engage in interactions with the robot. It was hypothesized that these features are minimal requirements for fostering effective social interactions between humans and robots. These findings suggest that for robots to be widely accepted and integrated into social environments, they must possess and exhibit a certain degree of expressiveness and attention, similar to what is expected in a human-human interaction. This, while increasing the engagement levels of the humans interacting, contributes to the naturalness and comfort of the interaction, facilitating smoother and effective communication.

2.3 Intent Communication

The previous sections showed how important it is to build trust and improve safety perception of the robot to enhance its interactions with humans. There are several ways [4] to achieve this, such as by proving the robot's competency to the people, by showing its warmth, that robot intentions are aligned with human interests and well-being, by designing the robot to appear or behave in more human-like manner (anthropomorphism). Another fundamental way to build trust in service robots, such as AMRs, is by communicating the intent [7] of their motion. AMRs such as an autonomous lawnmower, have little going for them in the anthropomorphism and warmth department, they are designed specifically for a task and often have to be efficient in it. So, we adopt the latter to build trust and to show its competence, by communicating its motion intention. Previous works [25, 13, 26] have done so by employing various modalities, from on-board projections to expressive lights to haptics to visual and sound. Some works [11, 27, 28, 12, 29, 10] also explore the use of movement as a modality to communicate intent within robots, this is especially interesting in our case, and in general, because it poses a small challenge in implementation and often builds upon the mental models of people's lived experiences. In other words, the simplicity translates to a low knowledge threshold, which is the goal.

2.4 Related work area

This section contains a brief explanation of the work conducted in a similar domain and how it relates to the work presented in this report. We attempt to provide a holistic view of existing research and discuss where the work presented in this report fits in the current landscape.

2.4.1 Autonomous Mobile Robot

Research conducted within HRI that focuses on AMRs is unique in that it is often times confined to specific use-cases and thus, the results obtained are seldom generalizable. Previous works [30, 31] that aimed to study human interaction with these robots did so in the context of a snow-clearing mobile robot and a mobile robot helping with logistics in an industrial setting. Of the two studies, only one (the former) tested with real-world scenario (albeit in VR). Furthermore, we noticed that, here, the research that focuses on intent communication and human perception of AMRs is scarce and context-specific and often restricted to direct interactions. Pelikan et el. [32] urge the need to study the interaction of co-present humans and autonomous robots, where the users are not directly interacting with the robot. There is a real gap in generalizable behaviours for AMRs that we aim to bridge with the current study. Apart from the fact that the robot we are working with will encounter humans in public settings, with varied knowledge levels, we also had to consider the fact that it is a non-humanoid robot, and we cannot leverage anthropomorphic features to improve human perception. We therefore turn to some intrinsic modalities that all robots ship with: movement and light. We explored work conducted within communicative movement and expressive lights in other domains such as AVs and AFFs and derive our implementations of behaviours from cross-domain research. Additionally, we leverage mental models that humans build upon through their lived experiences by developing movement behaviours that people would be aware of and could recognize.

2.4.2 Autonomous Vehicle

Autonomous vehicles is a broad field of research that spans multiple disciplines like computer science, robotics, artificial intelligence, electrical engineering, mechanical engineering, transportation and traffic engineering, ethics, and law. Each discipline contributes its unique perspective and expertise, driving the development of autonomous vehicles forward in a comprehensive and holistic manner. Within the transportation and traffic engineering subdomain, there is an area that deals with pedestrian engagement, this is especially crucial if we envision a future where self-driving vehicles seamlessly integrate with the traffic and are a substantial chunk of the fleet of vehicles on the road. To this end, intent communication of self-driving vehicles is crucial. Since they also operate in the public and encounter people with varied knowledge levels, the behaviours they exhibit cannot be complex. Previous works [23, 33, 34] explore this through visual, auditory, and physical modalities. For the visual method, they employ an LED strip that communicates the vehicle action intent, as in, what it will do next through a series of light patterns. A behaviour we derive upon in our work with the lawnmower in this project. A key observation here is that these light strips are placed at almost eye-level for the pedestrians, which makes it easier for them to catch the attention of the unassuming pedestrians, this is not the case with AMRs where they lie at a significantly lower eye-level.

2.4.3 Autonomous free-flyer

AFFs are an upcoming segment of robotic platforms that are capable of intricate flight capabilities that are suited for exploration, surveillance, and telepresence tasks. This makes the study of their movement, especially interesting because of its unconstrained nature. This poses a real concern to operators co-existing in the space or observers, since it is difficult to predict how the AFFs will move. Research in communicative movement with AFFs [24] explores manipulations to the motion primitives that make up the flight paths of the robots, like making an arc, anticipatory motion, easing in-and-out, etc. Their results indicated that the manipulations described in the work positively effected users' ratings of AFF usability, motion naturalness, and their sense of safety. This demonstrates the impact of communicative movement, something we looked deeper into during the current study.

2.4.4 Human-Robot Proxemics

For machines like AFFs and other robots that lack anthropomorphic and zoomorphic features, it is more difficult to convey the robot's state and intended actions. To tackle this, previous works [35, 36] have explored the impact of altering the robot's motion planning using proxemics-based cost functions that consider human spatial boundaries. Existing research in Human-robot Proxemics also explores how future proxemic behaviours can be designed for the robots based on how people distance themselves from the robots. The results of that study show how the likeability of the robot affects how people maintain distance with the robot. Other research in the area [37] proposes an egg-shaped human-sensitive field that humans don't like encroached upon. These results serve as a foundation when we develop the behaviours and interactions for the robot.

2.4.5 Multimodal intent communication

We have established how important intent communication is to build trust in robots and improve human perception, we have a look at previous works that attempted to leverage several modalities: from on-board projections to displays to haptics to movement. While we have previously motivated our choice of using communicative movement and expressive lights as the mode of intent communication, for completeness, we have a look at other methods researchers have employed and tested. Recent breakthroughs in effective human-robot interaction [8] see the use of multimodal interfaces to establish communication with the robot, such as voice, image, text, eye movement, haptics, and bio-signals like EEG and ECG. While these developments provide an insight into what the future holds for HRI, these are largely impractical to use on an AMR such as an autonomous lawnmower. We look further at other works that tested visual [26, 31, 13, 7], audio [26], and haptics [26] as a way to communicate robotic intent to colocated humans. While these modalities turned out to be effective in communicating robot intent, they were, again, unrealistic for the robot we were working with – a lawnmower that is outdoors and constantly encountering the public. We chose communicative movement as a modality because it did not require us to accessorize the robot, and past research shows tremendous promise in the area. Works [10, 11, 28, 27] in communicative movement have shown how effective it is to use movement to indicate something to the observer. Observers as young as six-and-a-half months can infer a mover's goals from both human and robot motion [9]. Repetitive movement is viewed as communicative movement if there is no immediate goal visible to the observer [10, 12]. Goal-oriented movement is viewed as a message-bearing action, and human observers often successfully infer the goal of the movement [11, 28, 27], these kinds of movements can be achieved by being predictable and being legible; these movements often build upon the existing mental models that humans develop through lived experiences.

2.5 Summary

Harmonious coexistence of humans and robots relies on trust and improving human perception of the capabilities of the robot. One way to achieve this is by communicating the state of the robot and its intended actions, which allows it to be perceived as reliable by colocated humans. This phenomenon is explored in several categories of robots using various modalities. We provide an overview of these works and how these can be extended to AMRs. We particularly look at communicative movement and expressive lights as modalities for intent communication. This choice is agreed upon due to the low-cost of integrating movement behaviours and the existing mental models of indicative lights that people would have developed through lived experiences. We also consider Human-Robot proxemics as a parameter to enhance human-robot interactions, as the distance maintained between the robot and the human has psychological implications. The work conducted in this project is novel in that it attempts to extend similar work conducted in other domains and build upon it by considering several factors such as human mental models, human-robot proxemics, multimodality of intent communication, etc.

Chapter 3

Interaction Design

One of the challenges we faced when developing interaction patterns for the robot was that we had to keep it "simple". Since the robot would encounter people with varying levels of experience with robots, the behaviours displayed by the robot could not be too complex. With this at the core and based on existing research, we developed four interaction behaviours for the robot to exhibit when it encounters humans.

These behaviours were mapped to real-world scenarios that the robot might find itself in. We constructed a 2×2 matrix covering the scenarios and assigned a behaviour for each scenario. As previously mentioned, we chose communicative movement and expressive lights as our modalities for communicating intent owing to their simplicity, first, and then the fact that humans pick up motion [9] and attend to light quicker [13] than other modalities.

With this, we delve deeper into the details of how we augmented the robot, both, structurally and behaviourally to achieve our desired interaction patterns. We divide this chapter into three sections, Hardware Design 3.1, Implementation 3.2, and Behavioural Design 3.3.

3.1 Hardware Design

During this project, we worked with HUSQVARNA AUTOMOWER® 550 EPOS, Figure 3.1. The unit we received from the company is a research unit that has a Raspberry Pi 4 that is pre-installed with the Humble distribution of Robot Operating System (ROS) and several ROS topics that allow reading the different sensors on the robot. For the lights, since we were restricted to using the Raspberry Pi for control and power, we opted for a 5V WS218B

LED strip. Apart from being the highest rated LED strip that a Raspberry Pi can support without external power, it is individually addressable, and has extensive community support for troubleshooting due to its popularity in personal projects.

Figure 3.1: HUSQVARNA AUTOMOWER® 550 EPOS: the lawnmower we worked on

The decision to place the LED strip atop the robot was motivated by two reasons: previous research details the importance of drawing attention [22] and a crude appearance of the robot affects human perception [16]. The lights had to be subtly placed and feel like one with the body of the robot. We could not have the lights protruding out of the general structure of the robot and the placement be as seamless as possible. We also had to ensure the lights could grab the attention of the human *looking down at the robot*. Therefore, we chose to run the strip across the top of the robot. Figure 3.2 depicts the final result.

3.2 Implementation

To implement communicative movement and expressive lighting on the robot, we developed a ROS package that facilitated remote control and provided a simple interface for managing the lights. For programming the light patterns, we utilized the `rpi-ws218x` Python library, which abstracts the complexities of programming the light interface. We opted to develop the package based on the subscriber-publisher to ensure ease of

Figure 3.2: Final Hardware, after attaching the LED strip to the robot

use and readability. Furthermore, the developed ROS package ran on the Raspberry Pi onboard the robot and could be controlled via SSH access. This phase of development involved navigating the complexities associated with embedded programming related to hardware permissions. The solution involved decoupling the interactions and writing a wrapper that enabled control of the two modules — remote movement and lighting. Figure 3.3 shows the process of how the two modules communicate with each other and how the complete interaction model comes together.

The LED strip connected to the onboard pins of the Raspberry Pi needs to access to on-device memory, which translated to allowing root privileges for the program, this in-turn blocks the remote drive package. We needed to devise a solution that could tackle both problems and thus, opted for a Client-Server paradigm, wherein the ROS package we built, `Enhanced Drive` acts as a middleman abstraction for relaying messages between the client (remote drive module) and the server (LED module).

3.3 Behavioural Design

To design behaviours that the robot exhibits when it encounters humans, we started by establishing scenarios where it might encounter humans. We were presented with a vague idea of where this type of robot might be used, e.g.

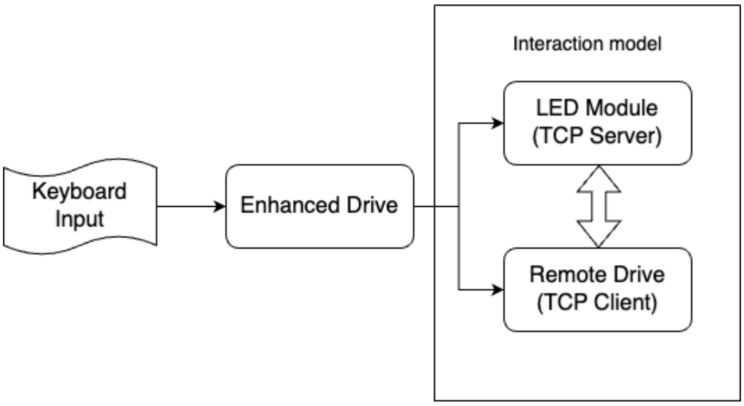


Figure 3.3: Process of how the interaction model communicates within the modules

large public parks and golf courses, and the fact that the robot may encounter people with varying levels of experience with robots. We used this information as a base and abstracted the different scenarios as described in Table 3.1.

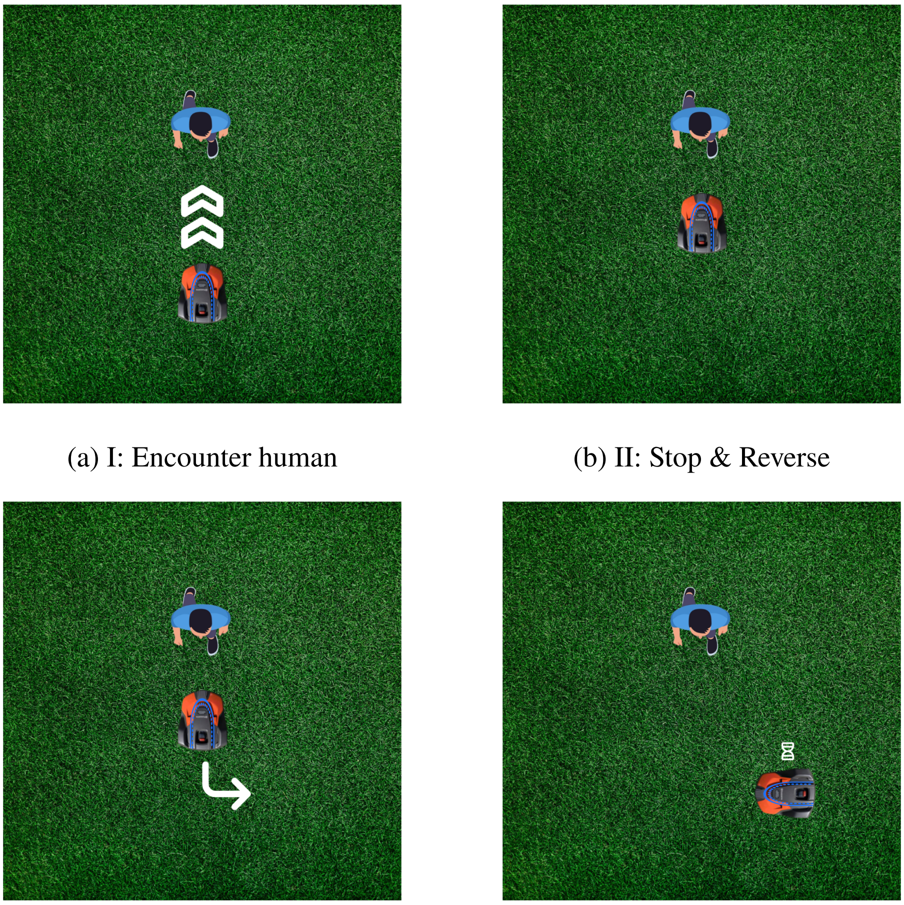
Scenarios	**Moving**	**Stationary**
Facing	The human and the robot are moving toward each other.	The human is standing in place when they observe the robot moving toward them
Not Facing	The human is walking in front of the robot.	The human is standing in place and the robot approaches them from behind

Table 3.1: Configurations tested

All the configurations are derived from the plausible real-world scenarios for the robot's operation. We develop interaction behaviours for the robot, where the goal is for the robot to communicate its intent of mowing the space that is occupied by the human. In its current state, the lawnmower does not exhibit any social behaviours and in scenarios discussed above, it would collide with the human and turn away to mow other parts of the park or the golf course. In the following subsections, we discuss in-depth the inspiration for all the interactions.

3.3.1 Moving-Facing

This abstraction is derived from the real-world scenario where a person walking through a park might encounter a mower in their way. We test a back-off strategy wherein the robot acknowledges the human and yields the way and waits for them to pass, thereupon continuing its job. Previous work [11] suggests that an explicit yielding motion is more legible and effective than a rudimentary stop-and-wait strategy. In addition to the movement cue, we use expressive lights to indicate, in real-time, what the mower is doing. This includes, indicating reverse motion, the direction it is reversing in, and the waiting action. The following series of images 3.4 highlight the interaction for this scenario.



(a) I: Encounter human

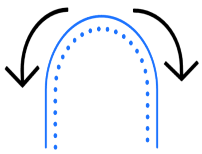
(b) II: Stop & Reverse

(c) III: Turn Right

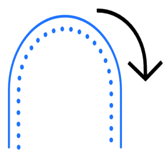
(d) IV: Wait

Figure 3.4: Movement interaction behaviour for yielding way (Back-off into a side)

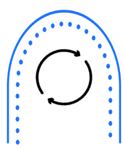
This interaction is complemented with expressive light patterns that indicate the various stages of the behaviour: reverse, turn to right, and wait for human to pass. These are depicted in the following series of images 3.5



(a) I: Reversing



(b) II: Turning Right

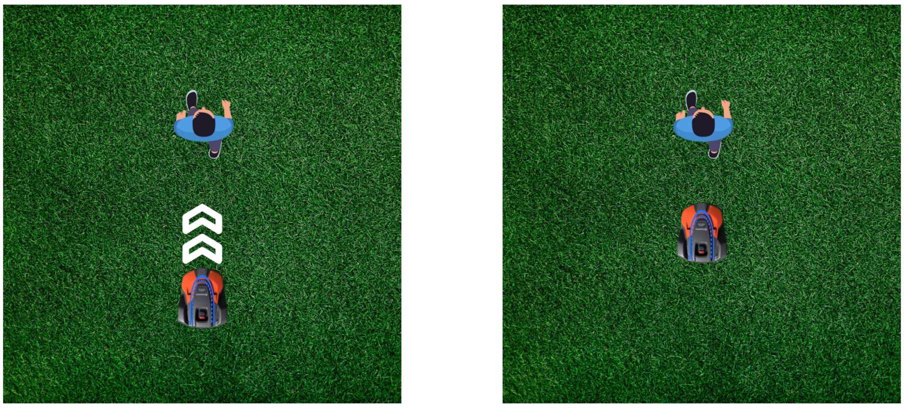


(c) III: Waiting

Figure 3.5: Light interaction behaviour for yielding way

3.3.2 Moving-Not-Facing

This abstraction is extended from the real-world scenario where a person is walking through a park and the mower is right behind them. The mower, in this scenario, will match the speed of the person walking and maintain a reasonable distance to them. We trade efficiency (by slowing down the mower) for improving perceived safety and trustworthiness of the robot. This decision was backed by the findings of previous research [37], where they determined a “human-sensitive” field. Which essentially translates to a range of distance to be maintained to ensure human comfort. The following series of images 3.6 highlight the interaction for this scenario.



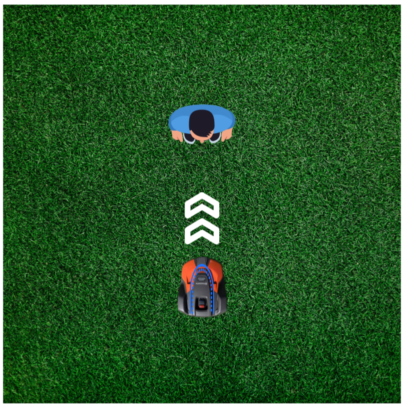
(a) I: Encounter human (b) II: Maintain Distance

Figure 3.6: Movement interaction behaviour for maintaining a safe distance

The Light pattern that complements this behaviour is a solid light. The mower remains active but reduces the speed to ensure it maintains a safe distance.

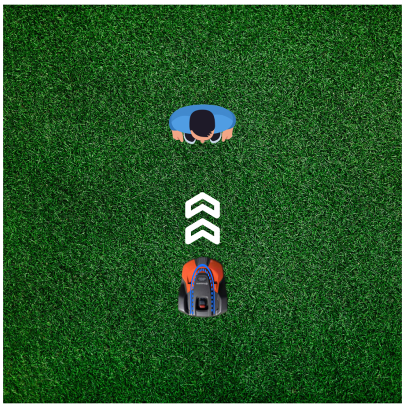
3.3.3 Stationary-Facing

The real-life inspiration for this abstraction is when a person is standing in a park and occupying the space that the mower wants to mow. The mower, in this scenario, will attempt to indicate its intent to mow the area by exhibiting a movement-based behaviour, complemented by light patterns. The robot repeats the motion three times to allow the human to grasp that it is trying to communicate. Based on previous work [10], humans tend to associate repetitive movement to a communicative intent, hence the repetitive behaviour. The following series of images 3.7 highlight the "Move Away" interaction for this scenario.



(a) I: Encounter human

(b) II: Pause & Reverse



(c) III: Go forward and repeat I

Figure 3.7: Movement interaction behaviour for suggesting human to move out (Back-and-Forth movement)

This interaction is complemented with expressive light patterns that indicate the two stages of the behaviour: reverse and go forward. These are depicted in the following series of images 3.8

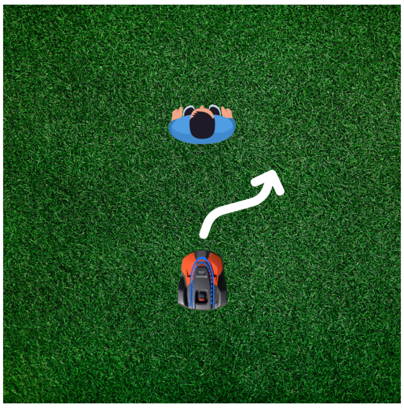
(a) I: Reverse

(b) II: Go Forward

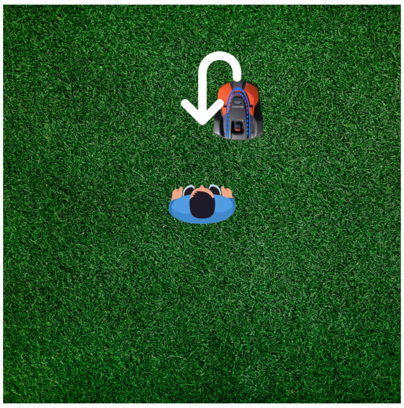
Figure 3.8: Light interaction behaviour for making the human move

3.3.4 Stationary-Not-Facing

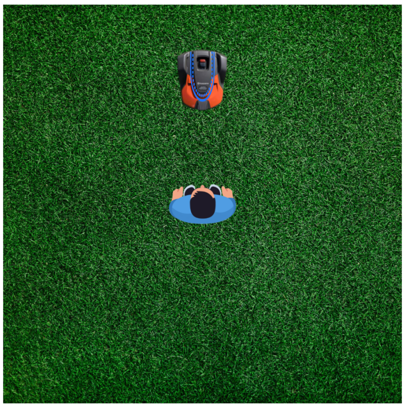
This abstraction is similar to the one above, except that the mower approaches the human from behind; i.e. the human does not see the mower approaching them. In this case, the mower manoeuvres around the standing human, while maintaining a safe distance to not breach the "human sensitive field" [37], to get in front of them and exhibits the behaviour discussed in the previous scenario (now that the mower is facing the human). The following series of images 3.9 highlight the interaction for this scenario.



(a) I: Encounter human & manoeuvres around



(b) II: Face the human



(c) III: Repeat ”Move Away” behaviour

Figure 3.9: Movement interaction behaviour for suggesting human to move out

The light interaction that complements this behaviour is simple. While the mower manoeuvres around the human to face them, it emits a solid light and once it is in front of the human, to initiate the “move away” interaction, it emits the same light pattern as in the previous section.

Chapter 4

Methodology

We conducted an online video study to assess the viability of the developed interaction behaviours. We recorded four videos, each depicting a scenario discussed previously, and used an online research platform to run the study. We collected both qualitative and quantitative data and ran separate analyses. We made use of thematic analysis techniques to assess the free-form responses and non-parametric statistical analysis for the Likert-type responses.

4.1 Research Process

We began by abstracting the different real-world scenarios that were used to develop the interactions into simple conditions. We recorded videos depicting these separately and developed a survey that consisted of both qualitative and quantitative questions. The survey is divided into different blocks that collect a wide range of data, from demographic information to assessment data for the videos. The survey was conducted through Prolific (www.prolific.com). For the videos depicting the interaction behaviours, the questions that followed were free-response and along the following lines.

- "Describe what the robot is doing."
- "What does the robot's behaviour tell you?"
- "What does the light on the robot tell you about the behaviour?"

The motivation for using free-form responses was to enable the participants to express what they thought about the mower's behaviour without limitations, since the objective of this project was to assess how successfully movement and light can communicate intent. Along with the qualitative data, we also collected quantitative data that aimed to evaluate how the mower displaying these behaviours would impact people's perception of it. We used a 5-point Likert scale to assess participants' safety and trust perception of the robot. These were based on the TiA [15] questionnaire and also included some statements A.1 pertaining to our research question.

An overview of the research process can be seen in Figure 4.1 below:

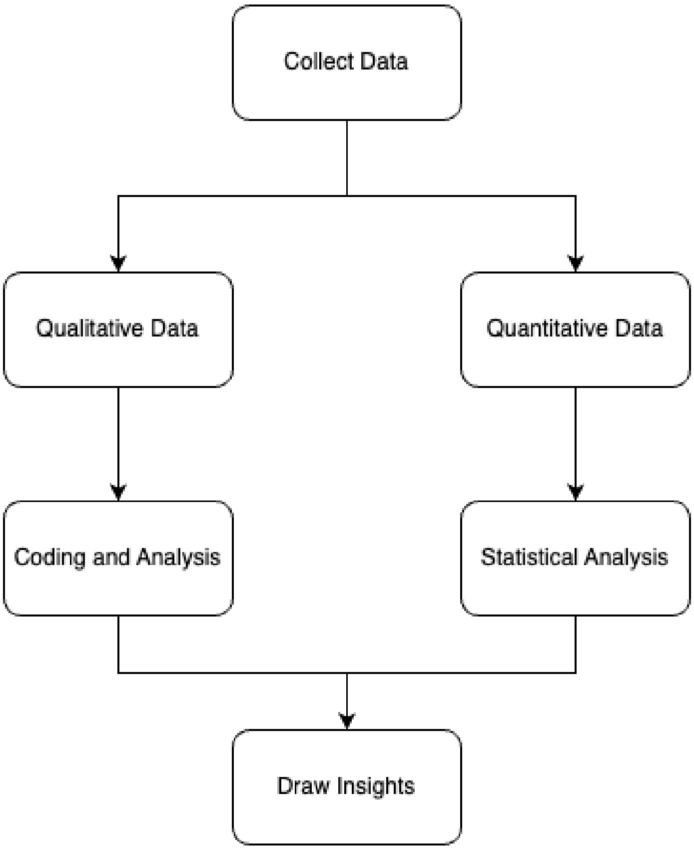


Figure 4.1: An overview of the Research Process

4.2 Data Collection

We used an online research platform, Prolific (`www.prolific.com`), to recruit people for the study, we decided to collect 300 participants for the study and paid them an average $9.00/hr for their time. The study took, on average, 12 minutes per participant to complete. The participant recruitment criteria specified a platform approval rating of at least 98% (from previous participations), prior participation in at least 20 studies, and at least 18 years of age. The participants were recruited from all over the world, where Prolific is available.

Privacy concerns are inevitable when it comes to handling user data. One way to mitigate these issues is to anonymize the data and remain GDPR-compliant when storing the data. The data we collect is anonymized in that, we drop the email fields and any identifying fields from the data. This is made clear to the participant when they agree to participate in the experiments. Each of the test subjects is given a consent form at the beginning of the study that informs them of how their participation would benefit the project and how the data generated and collected will be handled by us, the researchers. They are also given complete freedom in terms of participation and can choose to opt out of the experiments at any point, without motivation.

4.2.1 Sampling

We used a standard sample, distributing our study to all available participants. This was done to ensure we use a representative group to the final target group (which is essentially anyone who might encounter the lawnmower in public spaces).

4.2.2 Sample Size

We performed a power analysis to estimate the sample size needed for an experiment, given a required confidence level (90%) and a margin of error (~5%), plus leave room for bogus responses by collecting a buffer. This motivated the number of responses collected, 300.

4.2.3 Data validity

Furthermore, to ensure that participants were compensated appropriately for their time, we manually validate if they answered the survey questions, truthfully. Instead of using an attention check question, we relied on analyzing the responses to the open-ended questions and excluded possible bogus (low-effort) responses. We concluded that 6 of the 300 responses were either low-effort or incoherent, leaving us with 294 genuine responses.

4.3 Experimental design and Measurements

The Experiment, as discussed briefly above, consists of participants watching videos of the autonomous lawnmower exhibiting different operational behaviours and answering questions pertaining to these behaviours. The objective is to assess the capacity of these unique behaviours to impact human perception of the robot.

4.3.1 Test environment

The videos were recorded with a Panasonic 4K Ultra HD Camcorder HC-VX980, in a quiet room with one individual as the participating actor. The mower exhibits its behaviours around this individual. The videos are collected from an onlooker POV, the mower is wizarded during these interactions. The videos are then made part of an online survey consisting of a questionnaire asking to describe the behaviours and why do the survey-takers think the mower is displaying these behaviours. Furthermore, to assess how the mower exhibiting these behaviours impacts human perception, we include a 5-point Likert scale-type questions about trustworthiness, safety, and likeability.

4.4 Planned Data Analysis

Since our survey collects both qualitative and quantitative data, we split the analysis into two stages: Qualitative Analysis and Quantitative Analysis

4.4.1 Qualitative Analysis

For the free-response questions that followed the videos, we first cleaned them, coded them, and ran a thematic analysis. We make use of standard Python libraries, like spaCy, NLTK, and NetworkX, and visualize the data based on recurring themes and keywords. We make use of different text analysis techniques such as Topic Modelling, Sentiment Analysis, and Segmentation to draw insights into the data.

4.4.2 Quantitative Analysis

We collect 5-point Likert based data that assesses trustworthiness, safety, and likeability. For analysing this data, we use standard non-parametric tests owing to the nature of Likert-type data. Likert data is ordinal, has a fixed range, and is discrete. These properties violate the assumptions of most parametric tests. Non-parametric tests are accurate with ordinal data and do not assume a normal distribution. We use the standard Python library, SciPy, for running these tests.

Chapter 5

Results and Analysis

In this chapter, we present the results and discuss their implications. We begin by stating the demographic data of the participants of the study and further delve into how the explored interaction behaviours were perceived and whether they were successful in communicating robotic intent. As previously stated, we run a thematic analysis of free-form responses collected for each interaction and assess how the participants interpreted the interactions shown in the video. Furthermore, for the Likert-scale questions, we assess how important it is for robots to display social behaviours and if it has any impact on people's perception of the robot.

5.1 Demographic Data

As previously mentioned, we collected responses from 300 participants, of which 6 turned out to be bogus (low-effort) leaving us with 294 genuine responses, of which 146 were male, 142 were female, and 6 were non-binary. The mean age of the participants was 31.21 years, with a minimum of 18 years and a maximum of 68 years. The sample population was representative of the target population in that we wanted to capture how the interactions were interpreted on a wide range of experiences, which would be the case if the mower was out and about in the real world, where it would come across people from various backgrounds and lived experiences. Additionally, about 16% of the participants reported no prior experience with an AMR, about 9% of the participants reported extensive experience with AMRs, and about 75% of the participants reported "some" experience with AMRs.

Of the 294 participants, 145 had a Bachelor's degree, 83 had a High school diploma or equivalent, 60 had a Master's degree or higher and 6 had Less than a

High school diploma. We also collected participants' English proficiency level in order to check if that had an impact on how they interpreted the questions and answered. Of the 294 respondents, 9 reported to having a "limited working proficiency" or lower, upon inspecting the responses we decided to include (keep) these because the participants were able to still answer the questions even with broken English, implying they understood what was being asked.

Overall, the dataset is fairly balanced in terms of gender, the age range is broad, the majority of the participants hold at least a Bachelor's degree, and most participants report high proficiency in English. A visualization of the demographic data can be seen in Figure 5.1 below:

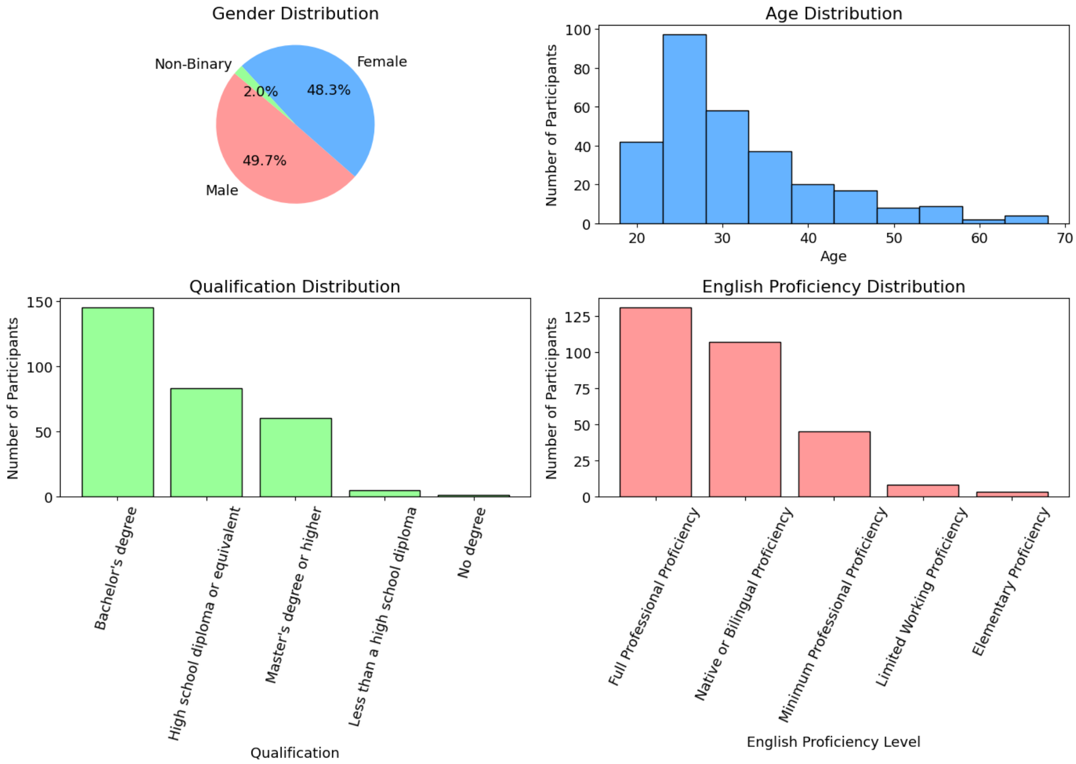


Figure 5.1: How the participants are split across the dataset

5.2 Interaction behaviours

For each of the interaction behaviours, the participants were instructed to watch the videos and answer the questions that followed. Each video followed four questions:

- *Describe the mower's behaviour*: A free-response question where the participants describe the motion of the mower, this enables us to verify if the participants actually viewed the video.
- *Do you believe the mower is attempting to communicate a purpose?* (Intent Check): A Likert-scale type question where we assess if participants could recognize the mower's attempts at communicating intent.
- *Describe your response to the question above, including your understanding of the robot's purpose/intention.*: A free-response question where the participants are free to describe their response to the previous question – either positive or negative.
- *Did you think the light behaviour shown by the robot was important and complemented its behaviour?*: A free-response question to gauge participants' impression of the importance of light behaviour shown by the mower.

In the following subsections, we will dissect the responses under each of the four interaction behaviour videos.

5.2.1 Interaction I

This interaction pertains to the mower "yielding way" to the human when it is on the same path as the human and the human is facing the mower. It does so by backing up and reversing into the right of the path the human is on and waiting for the human to pass. Participants in the study were able to largely describe what the mower was doing. A word cloud of the interaction description data can be seen in Figure 5.2.

The most frequent words indicate that participants mentioned "the robot's movements", "light behaviours", "detection of obstacles", and "responses to oncoming individuals by moving back and letting the person pass."

On asking if they think the mower was communicating an intent or a purpose, the majority of the participants "Somewhat agreed" (46.6%) that intent was communicated effectively during the interaction, followed by the next largest group that "Strongly agreed" (17%). Participants responded in affirmative that the mower was communicating to the human "to pass" as it made way for them.

Also, a large chunk of responses were either neutral (13.3%) or disagreed (23.1%) that the mower was communicating intent. Upon further inspection

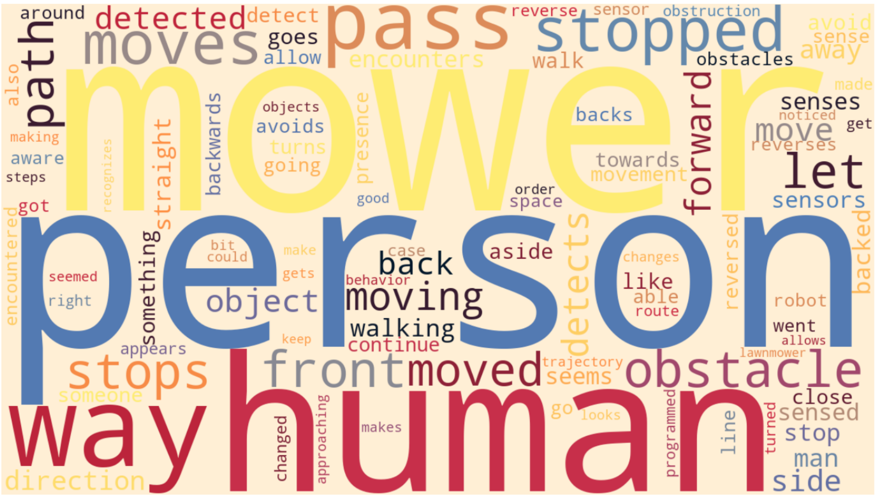


Figure 5.2: Top words in participants' description of the interaction

of what motivated their response, it appeared that people were confused with what "conveying a purpose" meant. Many of the responses indicated that the mower was "waiting for the person to pass", without realizing that that was the intended purpose of the mower's behaviour. Other responses attributed the mower's behaviour to its software program, stating "it was programmed to give way to humans" so it isn't the one communicating but the programmer through the mower. Others rationalized their "disagreement" by stating that the mower is a machine and can't communicate a purpose.

Additionally, we get an impression of how the participants viewed the light behaviour displayed by the mower during the interaction, while many respondents affirm the significance and presence of the light behaviour, there is a group of respondents that emphasize the importance of light for communication and safety. Lights were attributed as a means to warn or inform the human of its action (backing up into the right). Some responses also indicate that lights help to make the robot's intent more clear. There were several responses that linked the light behaviour to lights seen on a car.

Finally, to present an overview of the responses under each interaction behaviour, we code and categorize them for the reader; based on the most frequently occurring words, we create a repository of synonymous words for five categories of responses, including an "other" category for responses that don't fit anywhere. And, based on the presence of certain keywords (using the synonym repository), we categorize the responses. This is repeated for the rest of the interactions.

Table 5.1 consists of categorization of responses based on themes.

Category	**Count**	**Example**
Communication of Intent/Purpose	128	*"I think the robot showed the intention of letting the person walk in his path."*
Safety and Obstacle Avoidance	58	*"The robot did not wanted to inconvenience the human, that is why it stopped and parked."*
Other	49	*"Incapable of thought" / "JUST USING SENSORS"*
Task Performance	31	*"The robots purpose is to mow the lawn in a specific direction so by moving in that direction it is in a sense communicating its purpose."*
Lack of Communication	28	*"There is no communication being made, it is just an instruction that the mower has to get out of the way of an incoming person."*

Table 5.1: Categorization of different responses based on themes: Interaction I

Also, a combined overview of how participants responded to the "Intent Check" statement and the emerging themes for each of the interaction behaviours is depicted in Figure 5.6 and 5.7, respectively.

5.2.2 Interaction II

This interaction pertains to the mower maintaining a safe distance to the human when it is on the same path as the human and the human isn't facing the mower. It does so by detecting the human in front of it and matching pace and maintaining a safe distance to them. Participants in the study identified what the mower was doing and why. A word cloud of the interaction description data can be seen in Figure 5.3 below:

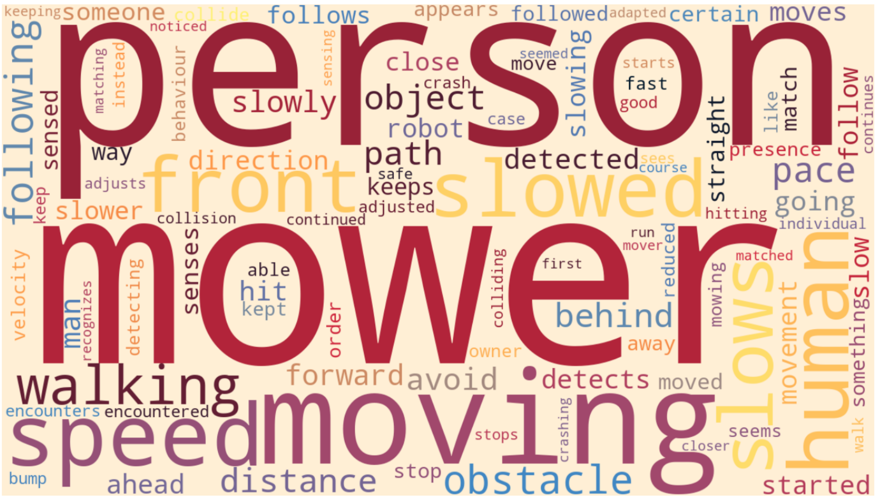


Figure 5.3: Top words in participants' description of the interaction

Participants recognize the mower's intent in "slowing down" and "maintaining distance" to the human, these emerge as common themes in the responses collected, among others that discuss "sensing movement" and "behavioural adjustment". The descriptions suggest that participants were able to perceive the mower's adaptive behaviours in response to its environment to ensure safety and collision avoidance.

On asking if they think the mower was communicating an intent or a purpose, one-third of participants "Somewhat agreed" (33.3%) that intent was communicated effectively during the interaction, followed by the next largest group that "Somewhat disagreed" (18.4%). Around 16.3% of participants "Strongly agreed", 14% "Strongly disagreed", and 18% were neutral. While some participants interpreted the fact that the mower was maintaining distance as it sensing the human and communicating that it "detects" human presence, other respondents that disagreed stated that the mower isn't communicating because it is "just avoiding obstacles". The responses that disagreed here follow the same trends as from the responses under previous interaction. The "it is a machine" and "programmed to do so" themes re-emerged for the respondents that did not think the mower was communicating intent by maintaining a safe distance.

Additionally, when asked about the light behaviour displayed by the mower during the interaction (a solid light without any change), many responded with a "No" but that it helped them realize that the mower was operational and "in motion".

Table 5.2 consists of categorization of responses based on themes.

Category	Count	Example
Safety and Obstacle Avoidance	98	*"it appears to just be slowing its pace so it doesnt hit the person"*
Communication of Intent/Purpose	85	*"The mower's purpose was to not crash into the person and keep a certain distance between it and the individual in front of it."*
Other	48	*"Programmed to do that" / "It is showing that it is able to follow instructions"*
Lack of Communication	38	*"I do not see any communication from the mower but a response rather."*
Task Performance	25	*"I believe it is just doing its job."*

Table 5.2: Categorization of different responses based on themes: Interaction II

Furthermore, a combined overview of how participants responded to the "Intent Check" statement and the emerging themes for each of the interaction behaviours is depicted in Figure 5.6 and 5.7, respectively.

5.2.3 Interaction III

During this interaction, the human in the scene is stationary, and the mower attempts to persuade the human to yield way for it to pass. The mower attempts to convey this by performing a back-and-forth movement in front of the human, indicating its desire to continue on its path. The mower performs the movement exactly three times, the reason for that is humans associate repetitive movement with communicative movement [10]. A word cloud of the responses describing the motion is seen in figure 5.4

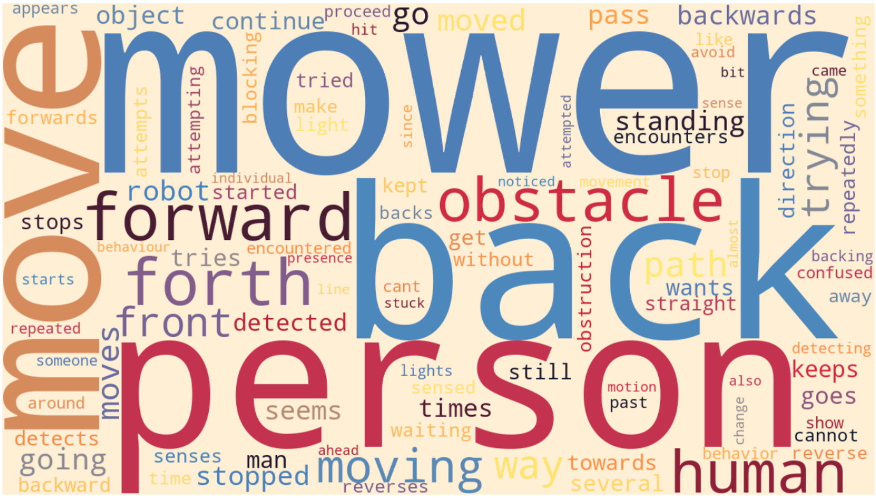


Figure 5.4: Top words in participants' description of the interaction

Participants of the online survey successfully realized the mower's attempts to convey an intention, with most participants "Somewhat agreeing" (41.5%) or "Strongly agreeing" (32.7%) that the mower is communicating something; 12.6% that were neutral, and around 13.3% that either "Somewhat disagreed" or "Strongly disagreed". Upon further investigation into the responses provided by the participants, it is clear that the interaction behaviour was effective in communicating the intent of making the human in the scene yield the way. Key themes that emerge during the analysis of the responses suggest that the mower wants to "move forward" and that the behaviour the mower is exhibiting is a direct response to someone "standing in the mower's way". Responses that attributed the mower's behaviour to its "software" re-emerged, with participants from that group suggesting that the mower is a machine and incapable of communicating independently.

Upon asking to reflect on the light behaviour shown by the mower, the participants pointed out that the lights indicated the direction of movement of the mower and most responses were in the affirmative about the utility of light in this interaction. Many responded that the light behaviour indicated what the mower was doing; the "reversing-light" pattern when the mower was moving back and the "forward-light" pattern when the mower was moving toward the human. And, in responses where participants couldn't understand what the lights meant, the mere fact that the robot was exhibiting those light behaviours enabled them to realize that the mower was doing "something" or trying to "grab attention".

Table 5.3 consists of categorization of responses based on themes.

Category	**Count**	**Example**
Communication of Intent/Purpose	149	*"The mower is probably trying to communicate to the person that it should probably move out of the way so it can continue with it's task"*
Safety and Obstacle Avoidance	59	*"The mower detects a human in its path and rather than colliding with the human it moves back and forth hoping the human/obstacle would move"*
Lack of Communication	44	*"Robot is programmed to pass humans/objects."*
Other	42	*"It is moving upon command"*

Table 5.3: Categorization of different responses based on themes: Interaction III

Furthermore, a combined overview of how participants responded to the "Intent Check" statement and the emerging themes for each of the interaction behaviours is depicted in Figure 5.6 and 5.7, respectively.

5.2.4 Interaction IV

This interaction is the same as in 5.2.3 except that the human in the scene is not facing the robot. Here, the mower manoeuvres around the human to get into their field of view and repeats the same interaction as in 5.2.3. A word cloud of the descriptions provided by participants is seen in figure 5.5

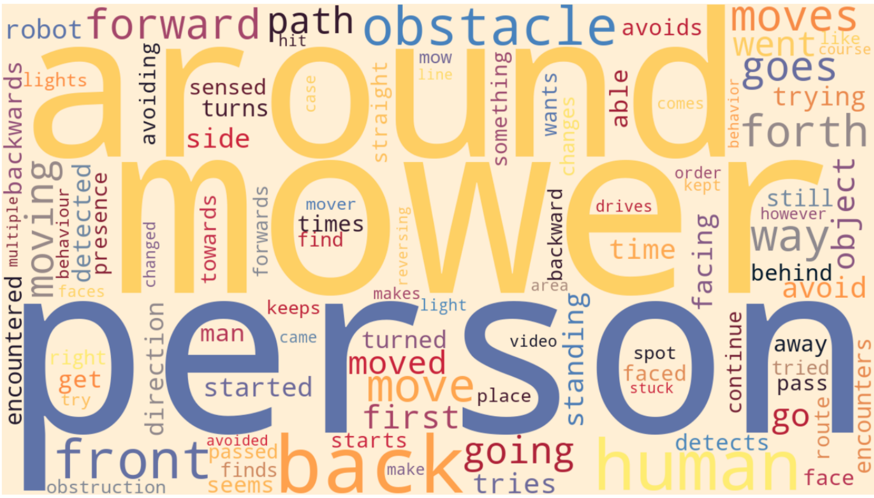


Figure 5.5: Top words in participants' description of the interaction

Based on the behaviour displayed by the mower, the majority of the participants subscribed to the idea that the mower was communicating intent. With 42.1% "Somewhat agreeing", 27.9% "Strongly agreeing", 14.6% "Staying neutral", and about 15.3% either "Somewhat disagreeing" or "Strongly disagreeing". Further inspection of the responses provided reveals that respondents were able to understand the mower's purpose and intention through its behaviour, the robot manoeuvred around the human to "be seen by the human", and it performed the back-and-forth movement for "the human to make path for the mower to work." While some assumed the mower's behaviour in turning back (toward the human, after going around them) as the mower needing "assistance". While some responses got it partially right in that, they attributed the mower's manoeuvres to just "avoiding collisions". There were some responses where the participants perceived the mower's behaviours as "malfunctions" because it appeared that, at first, the mower moved around the human to avoid collision but then turned back at them to continue the behaviour, which the participants confused as it "malfunctioning" because it was supposed to "avoid obstacles".

Furthermore, on inspecting how the light behaviour was perceived, many participants affirmed that the presence of indicative light complemented the mower's behaviour. For the light behaviour displayed by the mower during the back-and-forth motion, several participants suggested that it would allow them to know that the mower has "detected them". Several other responses stated that the light behaviour in this interaction was not significantly important as for the most part of the interaction the mower is facing the back of the human in the scene.

Overall, the responses were weak compared to the responses from the previous interactions. We believe the reason for this—the human in the scene is not facing the mower as it manoeuvres past the human (to indicate obstacle avoidance), and the next part of the video is the same as 5.2.3, which people have already seen and commented on, and seeing the same interaction in this context might be confusing some participants — why would a mower turn back (after avoiding the obstacle)?

Table 5.4 consists of categorization of responses based on themes.

Category	**Count**	**Example**
Safety and Obstacle Avoidance	108	*“Mover realised that person stood back to him. So this caused him to avoid the person and drive in front, to signal that he’s staing on his way of mowing.”*
Communication of Intent/Purpose	68	*“The mower is communicated with the person of its intention which is to mow where they are standing.”*
Lack of Communication	42	*“the robot does not seem to have a precise task and its behavior is apparently illogical.”*
Other	39	*“The sensor got activated and overtook the person in front.”*
Task Performance	37	*“The robot wants to move and mow where the person is.”*

Table 5.4: Categorization of different responses based on themes: Interaction IV

Furthermore, a combined overview of how participants responded to the “Intent Check” statement and the emerging themes for each of the interaction behaviours is depicted in Figure 5.6 and 5.7, respectively.

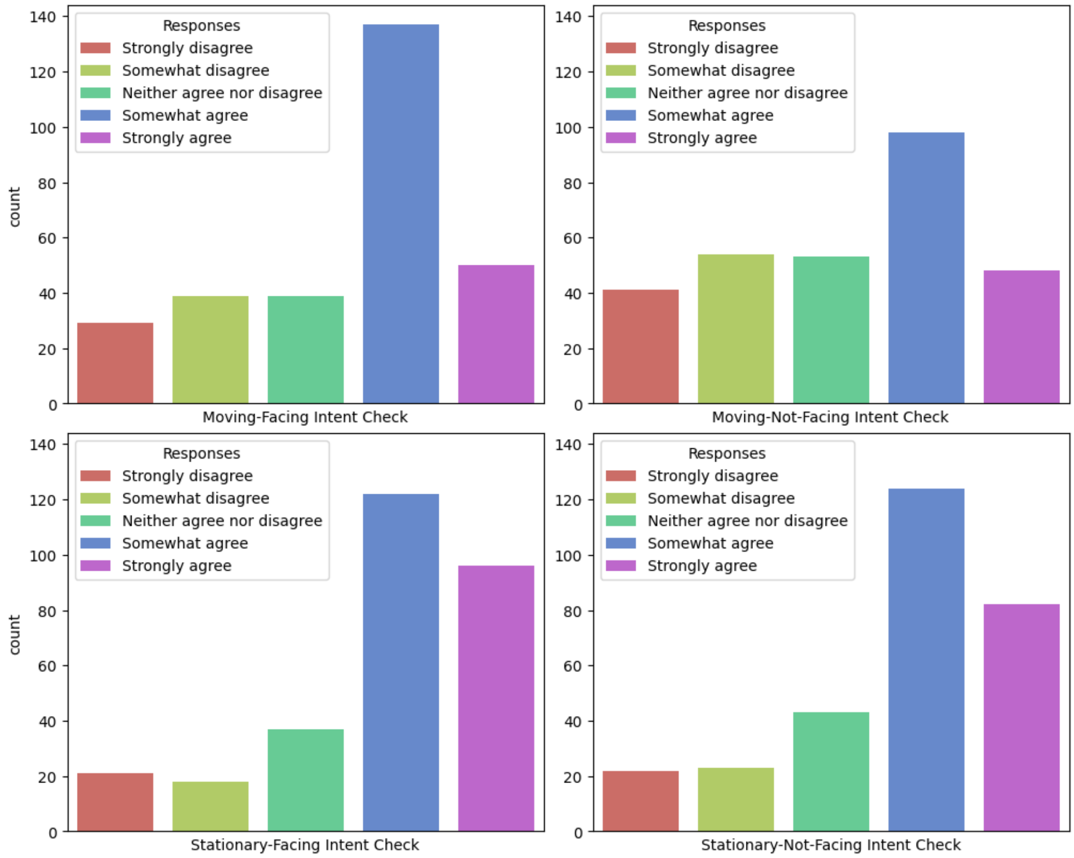


Figure 5.6: How the participants responded to the “Intent Check” statement across behaviours

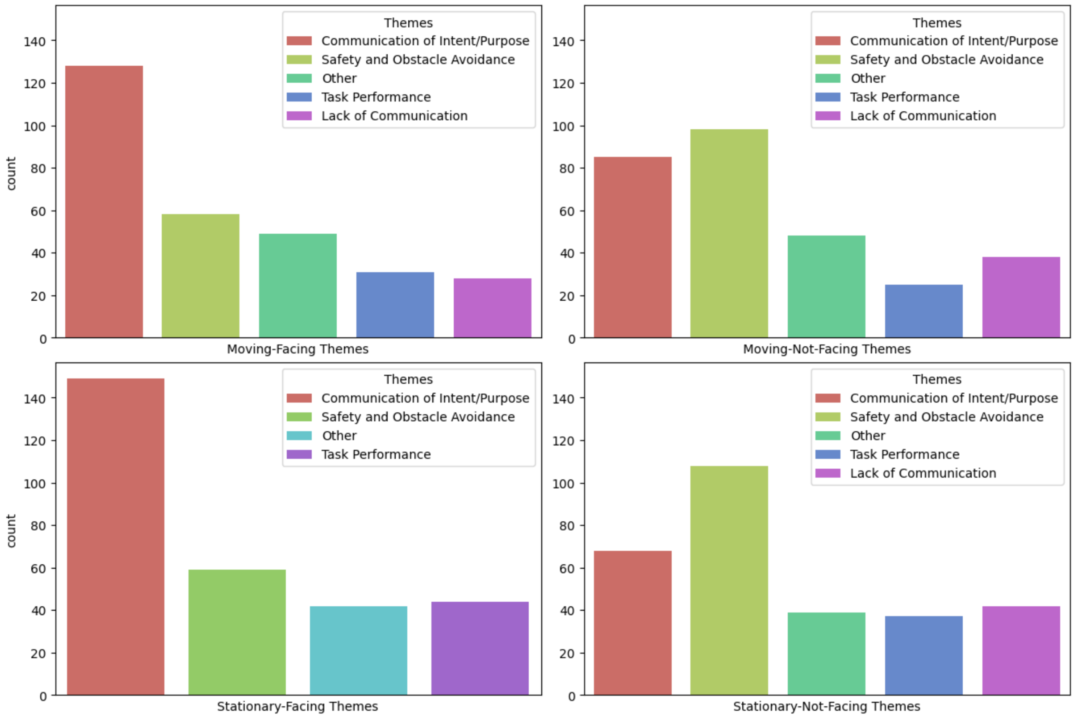


Figure 5.7: Emerging themes from participants' responses to the interaction behaviours

5.3 Significance of Social Behaviour

To evaluate the reliability of the responses collected pertaining the robot's display of social behaviour, we asked participants to rate the following statements A.1: *"This robot's behaviour improved my perception of it."*, *"This robot displayed socially acceptable behaviours"*, and *Knowing this robot's next move would make me comfortable when I encounter it in public spaces.*; combined with the questions above, regarding the feeling of safety and trustworthiness of a robot that exhibits social behaviours, we have five items that, together, signify the importance of social behaviour in improving people's perception of a robot. We compute the Cronbach's Alpha (α) = 0.86, which implies a high internal consistency, i.e. a high reliability for the responses collected.

5.4 Perceived Trust and Safety

In the next part of the questionnaire, we assess how important participants deem that the robot show “social behaviours”. We do this by using a 5-point Likert scale, where participants respond to statements that gauge the importance of robots displaying “social behaviours”. We use statements like, *“I could trust this robot because of the social behaviours it displayed.”* and *“I trust robots (in general).”* to assess the importance participants place on “social behaviours”. We repeat the exercise for the safety component.

5.4.1 Trust

We asked the participants if they would trust the robot *more* because of the social behaviours it displayed (`trust`), and if they trust robots, in general (`general_trust`) A.1. Their responses to these statements would allow us to evaluate how important they deem a robot show social behaviours.

Figure 5.8 shows a frequency plot of how participants answered. *1=Strongly Disagree* and *5=Strongly Agree*. We generate descriptive statistics of the two groups(`general_trust` and `trust`) to assess how they compare. While 50 respondents reported that they do not usually trust robots but would trust them more if the robots displayed social behaviours, the overall picture did not vary much for the full sample; for trusting robots with social behaviours versus trusting robots, in general, the median (IQR) for both categories was 4 (3-4). Furthermore, we performed a one-tailed Mann-Whitney-U test for the 294 observations to check if the distribution underlying `trust` is stochastically greater than the distribution underlying `general_trust`, we get ($U=55507.5$, $p<0.001$) suggesting that participants would trust robots who exhibit social behaviours more.

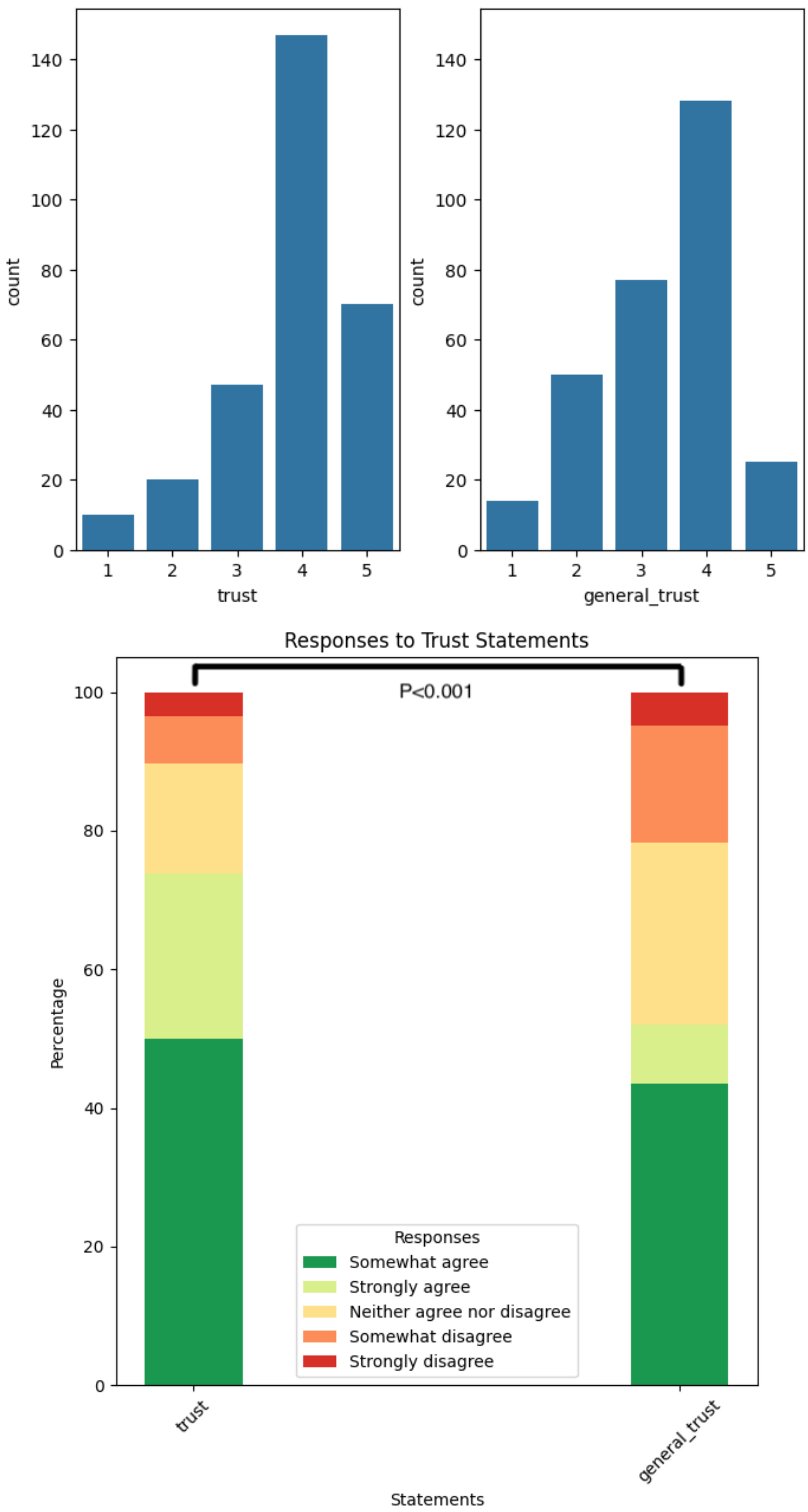


Figure 5.8: Participants' responses to *trust* vs. *general_trust* statements

5.4.1.1 Impact of Intent Communication

To evaluate if participants' responses to the statements were impacted by whether they were able to identify the mower's intent communication attempts, we separated the participants that were able to identify mower intent and those that couldn't, we then analysed their responses under the *Trust* section of the questionnaire. For participants that could identify mower intent, the median (IQR) for trusting robots with social behaviour was 4 (4-5), compared to trusting robots, in general, where it was 3 (3-4). We also performed a one-tailed Mann-Whitney-U test for the filtered data consisting of 221 responses and got (U=32904.5, p<0.001), indicating that participants who were able to identify mower intent reported they would trust a robot displaying social behaviours more. For participants who could not identify mower intent, the median (IQR) for trusting robots with social behaviour and trusting robots, in general, was 4 (3-4) for both cases. Performing a one-tailed Mann-Whitney-U test for the filtered data consisting of 73 responses results in (U=2915.5, p=0.146), indicating, for participants who couldn't identify mower intent, we cannot conclusively say they would trust a robot displaying social behaviours more.

5.4.2 Safety

Similarly, we asked the participants if they would feel safe around the robot because it displayed social behaviours (`safe`), and if they feel safe around robots, in general (`general_safe`). Their responses would help us assess how important social behaviours displayed by robots are for their safety perception. Figure 5.9 shows a frequency plot of how participants answered; *1=Strongly Disagree* and *5=Strongly Agree*.

Like with the *Trust* component, we generate descriptive statistics which indicate people feel safer around robots that show social behaviours, with a median value of 4 (IQR 4-5), compared to feeling safer around robots, in general, with a median value of 4 (IQR 3-4). Of the 294 respondents, 92 claimed that they would feel safer because a robot shows social behaviour compared to just feeling safe around robots, in general. Furthermore, we, again, perform a one-tailed Mann-Whitney-U test with the 294 observations to check if the distribution underlying `safe` is stochastically greater than the distribution underlying `general_trust`, we get (U=55690.5, p<0.001) suggesting that participants would feel safer around robots exhibiting social behaviours more.

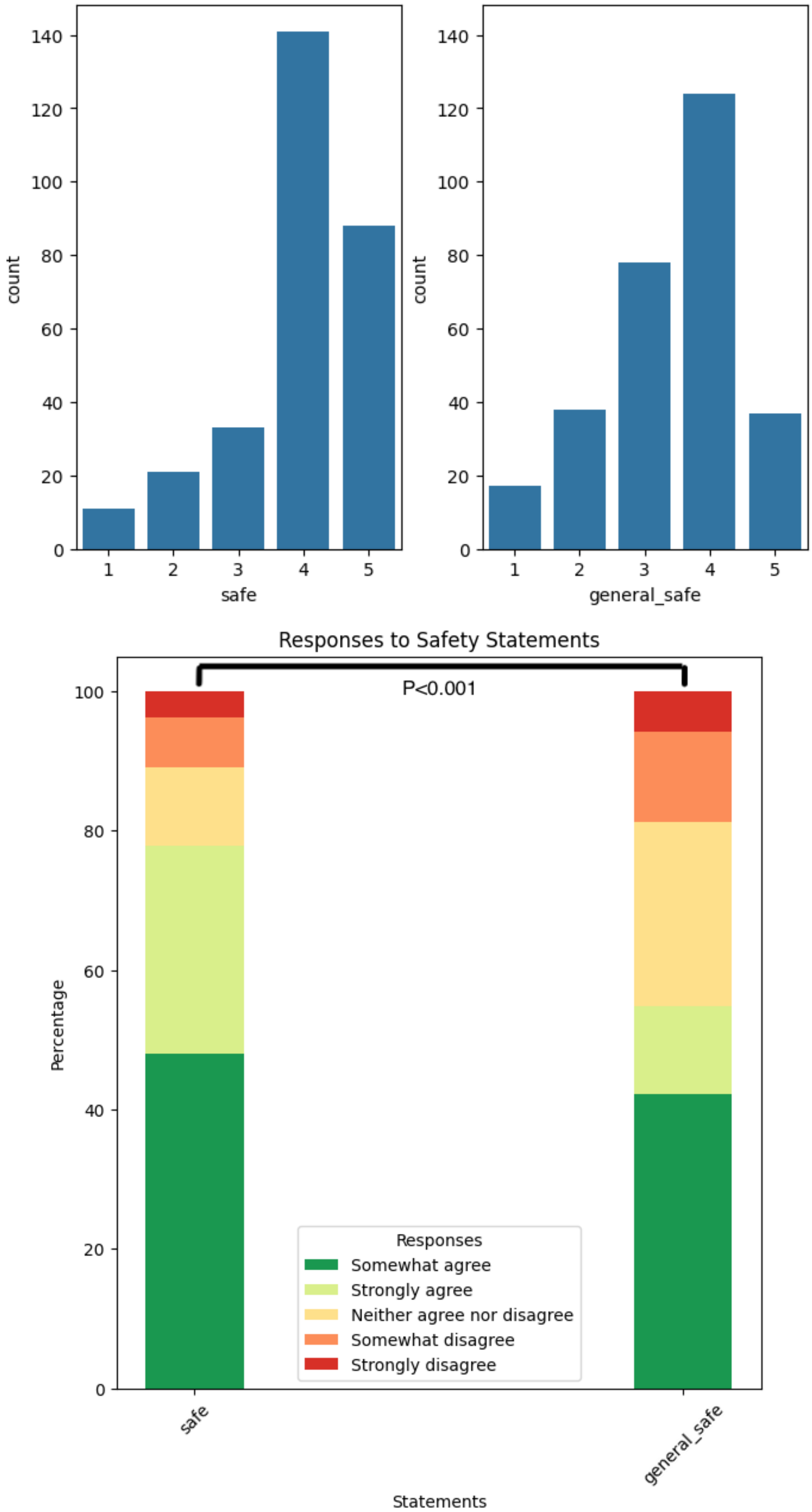


Figure 5.9: Participants' responses to *safe* vs. *general_safe* statements

5.4.2.1 Impact of Intent Communication

We perform the same analysis as for the *trust* component, and filter responses based on whether participants were able to identify mower intent or not. For respondents that could identify mower intent, the median (IQR) for trusting robots that show social behaviour and trusting robots, in general, was 4 (4-5) and 3 (3-4), respectively. A one-tailed Mann-Whitney-U test resulted in (U=32334.5, p<0.001), indicating respondents who identified mower intent would feel more safe around a robot showing social behaviours compared to robots, in general. Additionally, for participants who didn't identify mower intent, on average, the median (IQR) for feeling safe around robots showing social behaviour and robots, in general, were 4 (3-4), for both. A Mann-Whitney-U test gets us (U=3155.0, p=0.021), indicating that even people who couldn't identify mower intent, would feel safe more if they thought the robot was showing social behaviours.

5.5 Discussion

5.5.1 Relating to previous work

Through our study, we assessed the importance of intent communication and display of social behaviours in AMRs by developing interaction behaviours for a lawnmower for different scenarios and running an online video study. We presented the participants with open-ended questions regarding the developed interactions to gauge the legibility and effectiveness of the behaviours. The analysis of these responses revealed that three of the four interaction behaviours were described unambiguously by the participants, indicating that the behaviours were legible. On questions pertaining to the mower's intent, participants were, largely, also able to identify what the mower was conveying through its actions. These results were expected and corroborated with the findings from [11, 12] where the authors explored communicative movement to convey the intent to "Back-Off" and to "Ask to Follow". When faced with a stand-off, it was found that "backing off" was a more effective way to "yield way" than standing still and letting the user figure out [11], interaction behaviour I (one) we developed explored this with lights to complement the mower's actions. For interaction behaviour II (two), where the mower detects the human and slows down to maintain distance, participants were able to distinguish a change in the mower's behaviour stating it "detected" the human and "slowed down". This behaviour has its roots in the findings of *Lam et* *al.* [37] where they reported that there is a human-sensitive field, breaching which will result in the human feeling uncomfortable [37]; this field has a longitudinal length of ~4.5m, which is approximately the amount of distance we maintain with the human.

Furthermore, for interactions behaviours III (three) and IV (four), where the human is stationary, and the mower attempts to get the human to "yield-way" have their basis in the study of pet behaviours [38], which we noted after developing the behaviour.

5.5.2 Leveraging existing mental models

We complement the movement behaviour (back-and-forth) with lights. All the light behaviours developed to build upon existing mental models of people seeing light in the public, the waiting animation, the reversing animation, the side indicator pattern, were all developed keeping in mind people's lived experiences. The choice of an LED strip as the medium of light communication was motivated by recent studies in Pedestrian-AV communication [34, 23, 33]. While our light behaviours did not act as independent agents of intent communication, from the participants' responses, they seem to have effectively complemented the mower's movements. Indicating the "internal state" of the mower at times and communicating the "acknowledgement of the human" in the scene, according to the respondents.

5.5.3 Different importance of intent communication

It needs to be noted that the four interaction behaviours differ in terms of the importance of intent communication in their respective scenarios, while interaction behaviours I (one) and III (three) involve direct interaction with the human (human faces the robot), interaction behaviours II (two) and IV (four) do not, and are more of for the on-looker in the scenario. This explains the responses for the "intent check" statements under those interaction behaviours because the participants, probably, answer through the point-of-view of the human in the scene.

5.5.4 Agency Attribution

Overall, we observed a positive indication of recognition of the mower's intent and legibility of its action; there were responses that attributed the mower's actions to its "programmed behaviour" indicating that the mower, itself, is incapable of communicating intent, but it's the programmer who is responsible for its action. Agency attribution is a popular avenue of research in HRI [39], including a set of statements to evaluate agency attribution might have given us more profound insights into how people perceive these service AMRs. Especially since, the robot being used is not as anthropomorphized as a humanoid robot [40].

5.5.5 Two-dimensional analysis

Assessing the responses to the interaction behaviours in two-dimension (comparing facing/non-facing interaction behaviours) does not reveal new insights, participants were not less likely to identify mower intent when the mower faces the human than when the mower does not face the human. We believe this is due to the on-looker POV that the videos are shot with. The participants are watching the mower interact with person in the scene and respond accordingly.

5.5.6 Summary

For a robot that is "in the wild" and encounters new people daily, such as an autonomous lawnmower, development of socially apt behaviours is important. While the work discussed here pertains to a small subset of different scenarios that a lawnmower can encounter, it provides a basis for future work to build upon. Also, we restrict our "modes" of intent communication to movement and light, which can be extended to other modalities. Through this project and these experiments, we also verified the cross-domain applicability of movement based and light-based interactions which, previously, were explored in other types of robots and autonomous vehicles.

Chapter 6

Conclusions and Future work

We began this research project by asking how social behaviours displayed by an autonomous lawnmower affect how it is perceived by humans coexisting in its space, in the area of safety and trust. To this end, we developed scenarios of where people might encounter such a robot and developed different interaction behaviours, using expressive lights and communicative movement, the robot can exhibit to communicate its motion intent. These included special movement behaviours for the robot encountering humans that are moving/stationary and facing/not-facing the robot. We then ran an online study to assess how legible these movement behaviours are and to assess the overall importance that humans place on robots displaying social behaviours.

In the following subsections, we will discuss the conclusions drawn from the results observed, the insights gained, and an overall evaluation of the work conducted here. We will also explore the future work prospects in this area and look at different approaches one might take to tackle the problem discussed here.

6.1 Conclusions

Intent communication was the core component of this thesis. We explored intent communication through the means of communicative movement and expressive lights. We evaluated how a mower communicating intent (showing social behaviour) would affect the mower's perceived safety and trustworthiness. Through the experiments conducted to this end, we can validate the claim that people have a high tendency to trust and feel safe around a robot that shows social behaviours. Be it acknowledging human presence, or reacting to the human's action in the scene. Apart from developing and testing four interaction behaviours for their legibility and intent communication effectiveness, we also verified the cross-domain applicability of movement and light-based interactions, previously explored in other kinds of robots. These were the goals discussed in 1. Apart from this, we also show the importance of trust and safety in human perception of AMRs; which was our hypothesis.

6.2 Limitations

For a thorough understanding of how the developed interactions fair in the real world, we would have, ideally, liked to conduct an in-the-wild experiment with in-person participants interacting with the mower. This would have allowed us to gain insight into how people reacted to the said interactions. There were three limiting factors for not taking this path: one, the weather was unfavourable to conduct an in-the-wild experiment; two, the time allocated for this thesis project was short; three, and the most important factor, the ethical implications of conducting an in-the-wild study where we would be recording strangers interacting with the robot to collect data. This has serious privacy implications.

In terms of developing the research, we would have liked to explore several other modalities for the development of the interaction behaviours, apart from communicative movement and expressive lights, we considered the use of visual (screens, projections), auditory (speakers), etc. but due to limitation of time, we decided against the exploration of these modalities. Besides, setting up the mower with these would have led to significant structural changes to the mower which, in itself, would have affected how people perceived the robot [16]. So, any structural changes would have to be subtle and appear seamless.

Additionally, as previously mentioned, the detection of the scenarios was not autonomous, in other words, the mower was placed in different scenarios instead of it reacting to the scenarios and choosing appropriate interaction behaviours. The perception module for the mower is not explored by us and is left for future work.

Lastly, the intent communication model (behaviours displayed by the robot) are directed toward individual people in the same environment as the mower, group dynamics and specialized behaviours for conditions where multiple people share the environment are not explored, we again cite the limited time as the limiting factor.

6.3 Future work

The result of this work, apart from the insights into how communicative movement and expressive light in AMRs is perceived, is a repository of interaction behaviours for different scenarios an autonomous lawnmower can encounter. We tackle four such scenarios here, which constitute a small subset of interactions possible. The next possible step would be to extend the repository for group interactions with the mower, i.e. interaction behaviours for the mower encountering people in a group setting.

Apart from this, one could also explore other modalities for the interaction behaviours, some works make use of extra linguistic expression cues [41] to communicate a robot's internal state. The work involved interaction design using fluids, and is inspired from the use of graphical tropes used in animation, video games, and comics to improve a character's expressivity. Besides this, other forms of modalities such as haptics [26], projection [29], screens [7], audio [26] could also be explored in the context of AMRs.

In addition, similar work could be conducted, to check the viability of the interaction behaviours, with other AMRs. Also, to further improve context-aware navigational capabilities, the interaction behaviours of the AMRs could be coupled with Deep Reinforcement learning (DRL) approaches [42]. This particular method would allow autonomous robots to co-exist in pedestrian-rich environments and exhibit interactive capabilities.

6.4 Reflections

One of the main outcomes of the exploratory work conducted during this degree project is a repository of interaction behaviours that were developed to communicate robotic intent in the case of an autonomous lawnmower. In addition to the behaviours, we also validate the importance of robots showing social behaviours to engender trust and to be perceived as "safe" by humans. Implementing such "social" interaction behaviours in AMRs or service robots will lead to a higher degree of acceptance of such robots and will propel us toward a future of more cohesive human-robot coexistence. Like all technology, people have been slow to adapt to "service robots," and the work conducted here would allow us to better understand the barriers to adoption and develop strategies to enhance their integration into everyday life, improving efficiency and user satisfaction.

The thesis contributes to the United Nations (UN) Sustainable Development Goals (SDGs) number 9 (*Industry, Innovation, and Infrastructure*) by exploring movement and light as modes of intent communication and evaluating the effectiveness of these modalities in communicating robotic intent, which is central to a robot's safety perception and trustworthiness.

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Appendix A

Supporting materials

The BibTeX references used in this thesis are attached.

Source code relevant to this project and the Analysis of the user study can be found at https://github.com/shashankshirol/husq-interaction. Interaction videos used to run the study can be found at https://www.youtube.com/playlist?list=PLj-BwfDYlEDJR3rB5L8KTDM_3oyLOPdrt

A.1 Questionnaire used

Lawnmower on the Run - Main Study

Start of Block: Information Letter

Q1 Enter your unique Prolific ID

____

Q2 **Information letter for participants**
This text will provide you with some information about this study. Before partaking in this study, it is essential that you understand the procedure of the research and that you consent to voluntary participation. Please take your time to review this text.

Purpose of the research
The objective of the experiment is to evaluate how the behaviours portrayed by an autonomous lawnmower robot are perceived.

Procedure
This questionnaire consists of 4 sections, each section contains a video and a few free-form questions. The participant watches the videos and answers the questions. During the interactions, the mower encounters a human in various scenarios and exhibits a specific behaviour. The participants of this study assess these behaviours and describe their thoughts.

Risks
There are no risks in participating in this study and no negative side effects.

Duration
The total duration of the study is approximated to be 15 minutes.

Voluntary participation
The participation in this project is voluntary. You have the option to withdraw your consent at any time during your participation without giving a reason. All the information regarding you will be anonymized and deleted upon withdrawal from participation. There are no negative consequences to not participating or deciding to withdraw from the study.

Confidentiality and use, storage, and sharing of data
Your personal data will only be used for the purpose(s) mentioned in this information letter. We will process your personal data confidentially and in accordance with the data protection legislation (the General Data Protection Regulation and Personal Data Act).

Only the above-mentioned researchers will have access to your data. Project members include permanent and non-permanent staff at the KTH Royal Institute of Technology and Lancaster University, such as associate and assistant professors, post-docs, and master students involved in the project.
Your name or other sensitive data will not be recognized in publications.

The end of the project will be on 31-12-2024. At the end of the project, all the personal data will be either anonymized or permanently deleted.

Further questions and additional information
If you have any questions about the project or want to exercise your rights, contact: Shashank Shirol.

Informed Consent
- I have read and understood the information from the information letter for participants.
- I have had the opportunity to ask questions. My questions were answered sufficiently, and I had sufficient time to decide whether to participate.
- I understand that my participation is entirely voluntary. I know that I withdraw from the study at any time in the study without giving a reason.
- I know that my responses will be anonymized.

○ I consent to participate in this online study. (1)

○ I do not consent to participate in this online study. (2)

Skip To: End of Survey If Q2 = I do not consent to participate in this online study.

End of Block: Information Letter

Start of Block: Tell us about yourself

*

Q3 Enter your email

____

Q4 Select your Gender

◯ Male (1)

◯ Female (2)

◯ Non-Binary (3)

*

Q5 Enter your Age

____

Q6 Enter your highest qualification

▼ No degree (1) ... Master's degree or higher (5)

Q7 Please select your English Proficiency level

◯ Elementary Proficiency (30)

◯ Limited Working Proficiency (31)

◯ Minimum Professional Proficiency (32)

◯ Full Professional Proficiency (33)

◯ Native or Bilingual Proficiency (34)

Q8 Enter your previous experience with autonomous mobile robots (AMRs) (e.g. vacuum cleaners, lawnmowers, etc.)

- ○ No Experience (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ A lot of Experience (5)

Display This Question:

If Q8 != No Experience

Q9 Describe your experience with autonomous mobile robots (AMRs):

____

____

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____

____

End of Block: Tell us about yourself

Start of Block: Interaction 1

Q10
<Interaction Video 1>

Q11 Describe the mower's behaviour.

____

____

____

Q12 Do you believe the mower is attempting to communicate a purpose?

- ◯ Strongly disagree (13)
- ◯ Somewhat disagree (14)
- ◯ Neither agree nor disagree (15)
- ◯ Somewhat agree (16)
- ◯ Strongly agree (17)

Q13 Describe your response to the question above, including your understanding of the robot's purpose/intention.

Q14 Did you think the light behaviour shown by the robot was important and complemented its behaviour?

End of Block: Interaction 1

Start of Block: Interaction 2

Q15
<Interaction Video 2>

Q16 Describe the mower's behaviour.

Q17 Do you believe the mower is attempting to communicate a purpose?

- Strongly disagree (13)
- Somewhat disagree (14)
- Neither agree nor disagree (15)
- Somewhat agree (16)
- Strongly agree (17)

Q18 Describe your response to the question above, including your understanding of the robot's purpose/intention.

Q19 Did you think the light behaviour shown by the robot was important and complemented its behaviour?

End of Block: Interaction 2

Start of Block: Interaction 3

Q20
<Interaction Video 3>

Q21 Describe the mower's behaviour.

Q22 Do you believe the mower is attempting to communicate a purpose?

- ◯ Strongly disagree (13)
- ◯ Somewhat disagree (14)
- ◯ Neither agree nor disagree (15)
- ◯ Somewhat agree (16)
- ◯ Strongly agree (17)

Q23 Describe your response to the question above, including your understanding of the robot's purpose/intention.

____

____

____

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____

Q24 Did you think the light behaviour shown by the robot was important and complemented its behaviour?

____

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End of Block: Interaction 3

Start of Block: Interaction 4

Q25
<Interaction Video 4>

Q26 Describe the mower's behaviour.

____

____

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____

____

Q27 Do you believe the mower is attempting to communicate a purpose?

- ○ Strongly disagree (13)
- ○ Somewhat disagree (14)
- ○ Neither agree nor disagree (15)
- ○ Somewhat agree (16)
- ○ Strongly agree (17)

Q28 Describe your response to the question above, including your understanding of the robot's purpose/intention.

____

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____

Q29 Did you think the light behaviour shown by the robot was important and complemented its behaviour?

____

____

____

____

____

End of Block: Interaction 4

Start of Block: Perception and Trust

Q30 Answer the following questions based on your experience with robots and the videos you just watched.

Q31 Do you agree with the following statement:
"I could trust this robot because of the social behaviours it displayed."

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

Q32 Do you agree with the following statement:
"I trust robots (in general)."

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

Q33 Do you agree with the following statement:
"I would feel safe around this robot because of the social behaviours it displayed."

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

Q34 Do you agree with the following statement:
"I feel safe around robots (in general)."

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

Q35 Do you agree with the following statement:
"This robot's behaviour improved my perception of it."

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

Q36 Do you agree with the following statement:
"Knowing this robot's next move would make me comfortable when I encounter it in public spaces."

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

Q37 Do you agree with the following statement:
“This robot displayed socially acceptable behaviours”

- ◯ Strongly disagree (1)
- ◯ Somewhat disagree (2)
- ◯ Neither agree nor disagree (3)
- ◯ Somewhat agree (4)
- ◯ Strongly agree (5)

End of Block: Perception and Trust

Start of Block: Purpose of the study

Q38 Through this questionnaire, we wanted to assess the legibility and predictability of the robot's attempts at communicating the intent of its motion. Apart from this, we also hope to assess how safe or trustworthy the robot was perceived because of this. With your honest answers, we would be able to draw insights into communicative movement and expressive light which will help further bridge the gap toward a future of Human-Robot coexistence. Thanks for your participation.

End of Block: Purpose of the study

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