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Human-Approaching Trajectories for a Person-Sized Balancing Robot

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Fig. 1. Subject exchanging objects (red) from the white task location to the robot (yellow). Participants exchanged these “sensors” after each approach. The experimenter is to the left observing the interaction.

***Abstract*— This paper explores how a large, dynamic robot should approach humans in a collaborative task. We conducted a design study to understand the experience of collaboration and the perceived effort in collaboration. In the study, 15 participants collaborated with the ballbot, a heavy, dynamically-stable, human-sized mobile robot. The ballbot executed approach trajectories, reaching speeds up to 0.6 m/s. Participants found the experience of collaboration to be positive, and we discovered that a curved trajectory was not perceived to add effort to the collaboration.**

I. Introduction

Many robotics researchers are interested in creating robots for assisting humans in a variety of ways. These robots must be able to operate safely around humans and have a safe appearance; if individuals are not comfortable with a robot’s appearance and how it moves they may simply choose not to engage with it. In this paper, we explore *approach* in human-robot interaction with robots that have a dynamic trajectory. We propose that a relationship exists between the shape and speed of the trajectory that a robot traverses and a human’s comfort in interacting closely with that robot.

To understand that relationship, we work with the ballbot, a heavy, dynamically stable, human-sized mobile robot [1]. This robot has many advantages for human interaction, discussed in Sec. II. The ballbot, shown in Fig. 2(a), is a large (human-sized) robot, and although this gives the advantage of looking people in the eye, it can also be intimidating, as discussed in Sec. IV. We attempted to mitigate this effect, with the integration of a skin for the robot as well as appropriate trajectory planning while approaching humans. Our overall goal was to find out how people responded when the robot approached with curved and straight trajectories at a range of speeds to complete a collaborative task, as shown in Fig. 1.

II. ballbot

The ballbot [1] is an omnidirectional, dynamically stable mobile robot that balances on a single, spherical wheel. Seen in Fig. 2(a), it is an underactuated system that accelerates by leaning, but cannot directly control its lean angle. This makes motion planning and control nontrivial, but yields many benefits, especially for physical human-robot interaction [2].

Specifically, the robot is extremely compliant, due to the nature of balancing and its capability for omnidirectional motion. Despite its mass of 59 kg (weight of 130 lbs.), the robot can be pushed around using about 3 N of force, easily accomplished with a single finger. This compliance also allows people to stop the robot physically, if necessary. As well, dynamic balancing permits the ballbot to have a unique size and shape, namely being tall and skinny. The robot is the approximate size of a human, and as such is slender enough to easily navigate cluttered human environments.

Additionally, the robot has sensors at human eye-level, mounted on a rotating turret that emulates the function of a human head. These sensors include a directional microphone and speakers, which can be used to add another dimension to the ballbot’s interaction capability. The robot also has a laser scanner and RGB-D camera on the turret, both on a tilt assembly. This allows the ballbot to maintain real-time, accurate knowledge about the composition of its immediate environment, such as the presence of humans or obstacles. The ballbot deliberately has no expressive face or emotional display. Our research instead focuses on physical aspects of HRI. Despite having no “face”, the turret does imply an orientation which can be perceived as the front of the robot. The robot uses a Hukoyu UTM-30LX laser scanner at roughly waist height (.8 m) to perform localization, as many of the distinguishing features of the experimentation space (desks, platforms) only come up to that height. A map of

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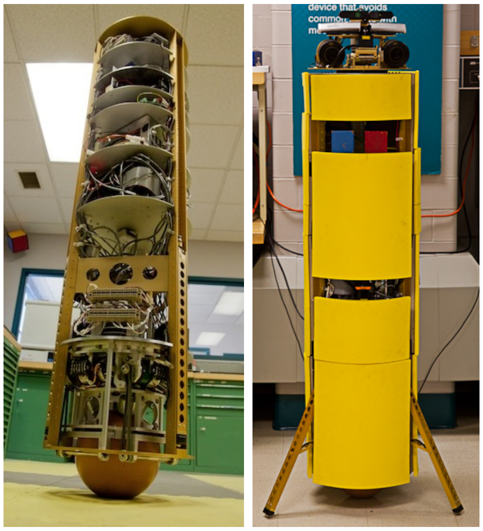

(a) (b)

Fig. 2. The ballbot: (a) balancing on its single spherical wheel; (b) with protective skin, blue and red blocks on object deck, and in a statically stable charging configuration (legs down).

the space was built prior to the study, and the robot used this laser sensor to localize relative to this static map, in order to determine its own position. This form of localization mitigates many of the problems associated with odometry drift (see Sec. II-C).

The ballbot has a navigation and control framework that allows it to execute smooth, graceful dynamic trajectories with arbitrary initial and final conditions. This type of graceful motion is paramount in human-robot interaction; humans tend to associate visually discontinuous, high-jerk movements with panic [3]. Additionally, the robot executing high-jerk motions during physical human-robot interaction may compromise stability margins which presents a potential safety hazard to the human.

The combination of all of these factors makes the ballbot an attractive platform for future physical HRI studies and motivates its choice as the platform for this study. The robot fulfills many of the standards for a human-robot interaction platform, as set forth in [4]; the ballbot is a reliable, physical system with many safety features that make it robust to a variety of failure modes (see Sec. II-C). Seen in Fig. 2(b), the robot is also outfitted with protective yellow skin panels, made out of a combination of Kydex^{TM}plastic and ethylene vinyl acetate (EVA) foam, for use in experiments. These panels provide protection for both the robot and the operators, as well as serving to cover up the inner circuitry and wiring making the ballbot appear less intimidating. The ballbot also has three independently-driven legs which retract into the body when the robot is balancing. The robot can extend the legs when charging its battery or not in use.

A. Control

The control architecture for the ballbot consists of a cascaded system, where the inner loop is a proportional integral derivative (PID) controller on the lean angle of the robot [1]. The lean angle set-point for this inner loop is set by an outer loop proportional derivative (PD) controller on the position of the robot's center of mass; the set point for this outer loop comes from a dynamically feasible trajectory generated by the high-level trajectory planner. This control system differs slightly from previous formulations [5] in that the outer loop control is now acting on the position of the center of mass of the system, as opposed to the center of the ball. This new formulation results in slightly greater variance in trajectory tracking, but allows for much better damping of large oscillations, as well as more compliance in the event of an unplanned collision.

B. Trajectory Planning

The trajectories that the ballbot executed during the experiments were generated by specifying waypoints with times and minimizing the crackle (the 5th derivative) of its flat output [5]. This flat output is a lower dimensional representation of the ballbot's state, allowing simplified planning that still satisfies the dynamical constraints of the system. Specifying a dynamically feasible trajectory for the full state of the system is very difficult because the ballbot is underactuated. The standard approach uses optimization to satisfy the system's equations of motion for a discrete time representation of a trajectory. Conversely, by formulating the system as differentially flat and using an appropriate representation of trajectories, only the boundary conditions need to be specified, and the resulting trajectory is guaranteed to be feasible. This method of trajectory generation is also much faster than sampling approaches, requiring less than 50 ms to generate feasible trajectories with multiple intermediate waypoints. By changing the times and positions of the waypoints, these trajectories can be custom-engineered to have certain curvatures and velocities, along with final positions. The ballbot can be made to approach human subjects along a variety of approach vectors, and at different speeds. In the study, the fastest trajectories peaked at between .6 and .75 m/s. The slowest trajectories peaked at .3 m/s, still faster than the .2 m/s that is common for social mobile robots.

The trajectories used in these subject trials had three waypoints: start, middle, and end. The start state was always determined by the state of the ballbot when the trajectory was generated. Likewise, the goal was always set as the collaboration location with a velocity and lean angle of zero. The trajectories were varied between conditions by changing the state of the middle waypoint and then generating the trajectory. By changing the angle of the middle waypoint with respect to the end waypoint and the desired speed at that waypoint, all four conditions could be met.

C. Safety

Due to the fact that the ballbot is a large, heavy robot operating around humans, it had to be robust to a variety of failure cases. At the highest level of control, the navigation framework had to be made robust to failure modes such as the loss of wireless network connectivity, bad trajectory tracking performance (possibly due to unplanned collisions), or loss of localization. In order to remain robust to these kinds of faults, the navigation framework only executed trajectories that took less than 2.5 seconds to complete. Larger trajectories were split up into smaller ones, and then executed; for each split trajectory, the planner would store a backup trajectory to bring the robot to a stop. If, between the execution of the shortened trajectories, an error condition was detected, the robot would execute the backup trajectory and bring itself to a halt, as shown in Fig. 3. Such error conditions could result from bad trajectory tracking, or due to a command from the operator. The display shown in Fig. 3 was shown in real time to an operator in an adjacent room. This operator was responsible for triggering the ballbot remotely to execute the next trajectory. This operator could force the robot to revert to the backup trajectory in the case of any unforeseen errors.

However, the potential for lower-level failure modes exists as well. To be fault-tolerant to these, the ballbot employs a hierarchical computing architecture. A low-level real-time operating system handles the critical balancing operation, while all high-level computation is done on a different onboard computer. Thus, if any high-level operation crashes (more likely than a low level operation failure) or in the event of a communication failure, the balancing performance of the robot is largely unaffected. The operator can safely stop higher level operations without affecting the stability of the robot. Additionally, the balancing controller will always decay the value of the last received lean angle command down to zero, if no new value is received, in order to avoid rampant acceleration in case of communication failure.

Fig. 3. Trajectories were planned and sent to the controller with a maximum execution length of 2.5 s (shown in blue). If the controller did not receive another trajectory, it would revert to a planned backup stopping trajectory (shown in red). Note that these trajectories are superimposed on the real scene in real time by an augmented reality technique similar to that of the first down line display in NFL football. The operator could see this display during the experiment.

III. RELATED WORK

There is a growing body of research that explores how robots should approach humans in social and collaborative contexts. Much of this work leverages knowledge developed in research on human-human interaction. In terms of social cues, the role of eye contact [6] and interpersonal spacing [7], in human interaction has been studied and leveraged in HRI. Research on interpersonal distancing in human interaction, also known as proxemics [8], has also been studied and applied to the interaction between humans and robots.

Applying Hall's zones of interaction to HRI [9], Walters et al. showed that most individuals prefer interaction with a robot in the "Personal Zone" (0.45 m to 1.2 m), although there was a significant minority of subjects who preferred the "Social Zone" (1.2 m to 3.6 m) [9]. It has also been shown that shared gaze and prior experience with pets can have a significant impact on how people feel about personal space while interacting with robots [10], along with the size of the robot and whether the interactant is seated or standing [11].

Researchers have also extensively studied collaboration among two or more parties. A seminal paper introduced the concept of coordination of context and content in communication, known as grounding [12]. The principle of least collaborative effort (also from [12]) asserts that parties in collaboration try to minimize the total effort spent on the collaboration. In human interaction, this can take the form of minimal utterances and positioning one's body to reduce effort and error. In human robot interaction, this has been interpreted to mean that a robot approaching a human to complete a collaborative task should not speed up or slow down erratically or zigzag [13].

In this work, we explore this principle in the context of dynamic trajectory planning. We build on the design principles presented in [13]: 1) face direction of travel, 2) avoid people's personal space, 3) keep a buffer around obstacles, 4) project the robot's own personal space, and 5) smoothly vary speed. Our goals were to create a trajectory design that allowed for fairly rapid changes in speed while maintaining a person's comfort in interacting with the robot.

IV. HYPOTHESES

We conducted a study in order to 1) understand the overall experience of collaborating with the robot and 2) ascertain if people experienced the robot's curved trajectory as contributing to more effort in collaboration. Our hypotheses were as follows:

1) A robot traversed along curved trajectories will afford more personal space in collaboration and therefore be rated higher than straight trajectories. This was motivated by notions of personal space and comfort with robots from [14] and [15].
2) Slower trajectories of 0.2 m/s will be experienced as safer and will be rated higher than faster trajectories of 0.6m/s. We believed that this would be the case due to the size of ballbot.
3) A robot traversing along curved trajectories will positively or negatively affect ratings of collaborative effort. This is due to the smooth increase and decrease in trajectory design, which supports the principle of least collaborative effort in HRI [13].

V. Method

To test our predictions about approach vectors and speeds, we conducted a design study in which participants collaborated with the autonomous ballbot to move a set of blocks between two stations.

A. Study Design

Participants were asked to work with the robot to move blocks between two collaborative workspace locations (white boxes in Fig. 4) set at a distance of 2.5 m from each other. The robot autonomously shuttled the blocks from one workspace to the other, carrying them on one of its decks (Fig. 2). At the active workspace (the workspace currently in use), participants retrieved one of the blocks from the ballbot's deck, and swapped it with a block on the workspace (Fig. 1). This signified the successful completion of the collaborative task.

The robot's approach vector and velocity were both varied between runs; the robot would approach the active workspace at .3 m/s or .7 m/s, taking either a direct straight approach or a curved approach which stayed farther from the participant. The curved trajectories respected all of the proximal zones of the subject (Fig. 5), whereas the straight trajectories did not. The robot selected goals and planned/executed the approach trajectories autonomously, while a human operator in another room issued **start** commands to the robot before each trajectory. This was necessary to ensure that the robot began executing its trajectories at the correct times, when the subject was in the proper position for the current trial to begin.

B. Participants

Fifteen participants (5 females and 10 males) were recruited through online postings on the university campus. All but one of the participants were native English speakers, and their ages ranged from 18 to 61. On average, participants rated their familiarity with robots as M=3.06 on a 7-point rating scale.

C. Procedure

Following informed consent, the experimenter introduced the participants to the ballbot, the workspaces, and the task (Fig. 4). Participants were told the fiction that they were collaborating with the robot to place "sensors" (the blocks) that measured electromagnetic activity, and that the "sensors" had a short battery life and needed to be moved to the robot to be recharged.

To gauge the subject's baseline comfort and familiarize them with the robot, four initial trials were conducted wherein the robot went to the task location first, and the subject was asked to approach the robot and complete the task. In the next five trials, the robot first moved to the staging area (A, E or C in Fig. 4) closest to where it had completed its last trajectory. This was meant to control the variance in the trajectories, and produce repeatable results. If the robot was at location B for the previous task, it would move to staging area C (shown with a solid line). From this staging area, the robot planned a trajectory towards the opposite workspace. Curved trajectories would always switch sides (A to B), while straight trajectories would preserve sides (E to B). In order to ensure that the robot did not collide with the subject, the subject was directed to the side of the workspace that the robot was not approaching. The robot then executed the planned trajectory and approached the workspace, maintaining an orientation facing that workspace. Upon the robot's arrival, the experimenter instructed the subject to complete the task.

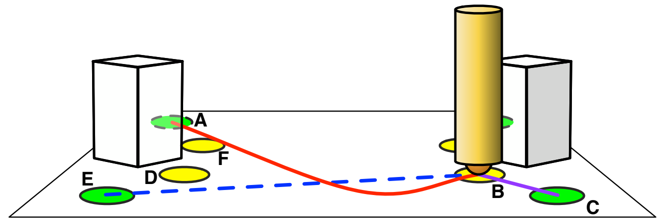

Fig. 4. Experimental Setup - Shown in red is a curved path, in blue a straight path. Yellow ellipses are the goals that either the robot or subject would go to. Green ellipses show the staging areas that the ballbot would move to between approaches.

Participants completed a pre- and post-study questionnaire to evaluate mood and did a post-study interview so that we could understand their experience of interacting with the ballbot and their perceived effort in collaboration. After each trial, the participant was asked to evaluate their relationship with the robot on a 5-point scale by answering a question on an Apple iPad handed to them by the experimenter. Interactions with the robot were also video-recorded during the trials for analysis of body language and proxemic cues.

Fig. 5. The curved trajectories planned and executed by the ballbot respect intimate and personal zones of the subject, whereas the straight line paths do not necessarily do so. Proximal zones are shown around subject: Intimate - Orange, Personal - Green, Social - Red

D. Analysis

We gathered both quantitative and qualitative data from our study. In terms of quantitative data, we gathered a number of successful transfers and survey data including ratings of the robot and numerical responses from the survey. We coded video data for distance from the robot, orientation

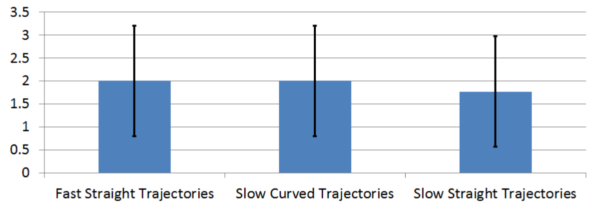

Fig. 6. Mean and standard deviation of reported comfort level over trajectory types for all participants (5 trajectories per subject). A score of 4 represents a high comfort level around the robot, while a score of 0 represents a low comfort level.

of the participant's head and body, and we gathered interview responses as measures of impressions of the robot. These data were thematically coded to reveal our participants' overall experience of collaborating with the ballbot and the role of a curved trajectory in collaboration.

VI. Results

All 75 transfer trials over 15 subjects were completed successfully, moving a block from the robot to the shared workspace, indicating successful collaboration. In terms of distance from the robot, we saw little variance in how close people stood to the robot over the five transfer trials. However, we noticed that participants oriented their heads and bodies to angle or face directly towards the ballbot in transfer trials 2-5. This happened in about 70% of the trials over all participants in examination of behavior for trials 1-5, regardless of trajectory.

Our first hypothesis predicted that participants would rate curved trajectories higher than straight ones. This was not the case. While participants rated the curved trajectories higher than straight trajectories, the large standard deviations associated with these data suggest that the result is not statistically significant (Fig. 6).

Due to the fact that the ratings for the preferences for these three trajectories were very close, we sought to understand if participants could discern the difference between the trajectory curvatures. In descriptive comments, about 25 percent of the participants described differences in the robot's paths. One participant stated, "I did notice some difference between the trajectories. Sometimes the robot makes an S trajectory, sometimes it goes directly from that side to the near side." Another stated, "It seems like it took a different route at times. A straight line, then veered toward me."

Our second hypothesis was that slower trajectories would be perceived as safer than fast ones. We did not find evidence to support this hypothesis. The robot's trajectory, even at its slowest point, was faster than the average 0.2 m/s speed for most assistive robots. It ranged from 0.3 m/s to 0.7 m/s at its highest speeds.

The survey showed a mean rating of 6 for the statement "I would feel comfortable standing next to Ballbot when it is moving slowly" and a mean rating of 5.05 for the statement "I would feel comfortable standing next to the ballbot when it is moving quickly," However, qualitative results reinforced that people felt comfortable around the robot when it traversed at fast speeds: "I would want it to move faster." "I think I could collaborate well with the robot, but I think it operates a bit too slow." "I think if the robot were sped up, I could walk with it." We interpreted this to mean that people were comfortable with the speed of the robot and the variance of speed in collaboration, even requesting that it go faster.

Our third hypothesis was that because of the smooth trajectory design, curved trajectories would either positively or negatively affect ratings of collaborative effort. We found evidence supporting this hypothesis. Participants made comments that referenced a positive sense of collaboration in their interviews: "We were getting something done; it wanted it done; I wanted it done." Four of fifteen participants desired the robot to have a more human-like appearance and behavior.

These lifelike and social attributions towards the robot also serve as a measure of positive collaboration [16]: "The robot plans its motion kind of like a cat. The motion of the robot was similar to my cat, playing fetch." "It's not completely human, but clearly it's able to interact and collaborate." The turret with its camera and two round speakers was interpreted as a head with a face and large eyes. "[The head] gives the impression of human ears and human eyes, like he is looking at you even though he is a robot." All of these measures suggest a positive experience in interacting and collaborating with the robot, therefore not supporting the rule of least collaborative effort for a robot with curved trajectory or one that changes in speed.

Our analysis of the video recordings showed different behaviors across the straight and curved trajectory trials. When the robot moved using a curved trajectory, we saw consistently that people turned earlier to face the robot in the collaborative task, stepped toward the robot more frequently, and more consistently turned their bodies toward the robot to complete each block transfer task. This could indicate that a curved trajectory could be best for a task that is both social and collaborative. Participants noticed and commented on the curved trajectory, making social attributions about it: "It wasn't moving straight to that location; it moved to the side first." "It never really got too close like it was kind of shy." "Sometimes it took the direct route. Sometimes it's heading another way and changes direction." "It took a different route at times. A straight line, then veered toward me."

VII. Discussion

In this paper, we present a design study to understand the overall experience of collaborating with the ballbot, and to understand the role of a curved trajectory in contributing to more or less effort in collaboration. We found that straight trajectories were rated higher than curved ones, although curved trajectories were not found to help or hinder collaboration, despite the fact that people oriented to the robot differently in the curved trajectory trials.

The principle of least effort in collaboration has been interpreted in human-robot interaction to mean that collaborative robots should move in straight trajectories at steady speeds. Our study shows that a curved trajectory of varied speed has no difference in ratings of collaboration. This is an area for future study.

Additionally, we predicted that slower speeds would be perceived as safer for collaboration with the robot. We did not find this to be the case. Possibly due to the design of the robot, people did not feel uncomfortable with the faster speed. The majority of subjects were of the opinion that the ballbot should have gone faster than the "fast" trajectories. This is also an area for future study. Would they have the same opinion of statically stable robots, or is it due to the fact that the ballbot is a balancing platform?

We hope to conduct more research to refine these initial results, and understand how they may extend to other robotic systems. We hope to understand how to design robots that could vary their trajectories based upon whether people are interacting with the robot once or repeatedly, and whether the task is purely functional or if it has social aspects. We found that subjects became disinterested if the speeds were too slow. Motion design and speed might be used to improve a sense of collaboration, effectiveness, and perceptions of competence and sociability.

VIII. Limitations

One factor in the study with an unknown effect was the presence of the experimenter in the room who directed the subject and held the iPad. Because the experimenter was at ease with the robot, this may have artificially increased the comfort level of the subject. Additionally, the context of our study—motion planning for a dynamic robot that moves on a ball—may seem non-generalizable. However, other ballbots are being created and some of these robots are moving into real-world applications. Whether our results will generalize to other robots is at present unknown.

IX. Conclusions

We have presented a design study using the ballbot robot, a person-sized balancing robot which features dynamic trajectories. We looked at subjects' body language, reported comfort levels, and behavior as observed in videos made during a collaborative task. Video analysis and qualitative comments made during and after the collaboration indicated that while participants rated the straight trajectories the highest, they were comfortable with curved approach trajectories (none of which entered the subject's personal zone) and with the experience of interacting with the robot overall.

The effect of varying speeds of approach was also studied. The maximum speed of .6 m/s was described as too slow for the collaborative task. While the difference was noticed, there was no discomfort with peak speeds or variance in speed. Additionally, the findings of [15] were confirmed, in that subjects overall became more comfortable with the robot over the course of the experiment.

Finally, the experiment was a successful step in our program of pursuing physical HRI research with the ballbot. Furthermore, all participants reported having no fear of the robot, which we consider to be successful in the safety and control of the system.

X. Future Work

We are also interested in further exploring collaboration as expressed through trajectory shape and speed. One idea is to perform a similar study at significantly higher speeds, attempting to find the maximum speed at which people are comfortable collaborating with the robot. This is challenging, as increased speed corresponds to an increase in risk. We can add other design features, such as speech synthesis and recognition capabilities in conjunction with facial tracking, to enrich the experience of the collaborative process. Future studies will also likely incorporate both social and functional tasks. We may also perform collaborative studies with curved trajectories using a smaller ballbot.

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