Classifying Human and Robot Movement at Home and Implementing Robot Movement Using the Slow In, Slow Out Animation Principle

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***Abstract*—We examine how robot movement can help human-robot interaction in the context of a robot helping people over 60-years old at home. Many people are not familiar with a robot moving in their home. We present four movement conditions to classify movement between a human and robot at home. Using phenomenology and familiarity, we recognize some of these conditions from other interactions people have with other moving things. Using techniques from animation in movies, we give to the robot a distinctive style that can make the robot's movement more familiar and easier to understand. Further on, we examine animation and present how to implement the animation principle of slow in, slow out with a research robot that can control its speed. We close the paper with future work on how to use the classification system, how to build on the slow in, slow out principle implementation for animated robots, and an outline for a future experiment.**

Keywords*–*human-robot interaction; animation; style; movement; slow in, slow out.

I. Introduction

In previous work [1], we saw that projections for people over 60-years old who will not be working (hereafter "the elderly") will be larger than the number of people working [2]. As people age, they tend to accumulate different aches, pains, diseases, and disabilities. The elderly will need assistance to continue to live independently with these acquired health issues. This aid could be a robot with sensors that could help monitor and assist the elderly person staying at home. If robots will be in homes, elderly and other people need to easily interact with the robots. We posit that making robots move distinctively using techniques from animation could make this interaction easier.

Previously, we used phenomenology to examine movement and classified robot movement in the home into classes [1]. We also discussed robot movements in the frame of proxemics [3], people's familiarity with robot movement, and animation techniques that could help make the movement more familiar. In this paper, we build on the previous work [1] by further exploring the topics of familiarity and proxemics, before introducing a formalized version of robot movement and a possible way to animate it using the animation principle of *slow in, slow out*. This contributes a combination of the phenomenological and the formalized exploration of moving a robot using an animation technique. This gives us a starting point for building future work on human-robot interaction (HRI), such as experiments or user evaluations.

We first present the context by examining robots for helping the elderly and robot's movement in the home (Section II). Then, we discuss robot movement and what animation and style means for robots and HRI (Section III). To make it easier to look at robots and human movement, we present a framework for classifying movement relations between a person and a robot (Section IV). We use this framework to aid in looking at the concept of familiarity and how robot motion compares to the motion of other objects people encounter in everyday life (Section V) and how animation can help with this familiarity. Then, we present a formalized version of robot movement and how to derive slow in, slow out movement from it (Section VI). Finally, we present ideas for future work (Section VII) before concluding the article (Section VIII).

II. Research Context: Robots at Home

Western countries are examining the issue of the "elderly wave" [2]: the number of people who will be retiring and needing care will be larger than the people entering the workforce for these jobs. There is a need for the elderly to live independently at home longer. Living at home as long as possible is also the wish of many people. One way of addressing this goal is to use *welfare technology* that can assist the elderly [4]; this includes technology like the Internet of Things and smart home sensors for reporting and helping elderly complete tasks [5][6]. Sensors can also provide a warning when things go wrong, such as an elderly person falling [7].

Instead of mounting the sensors all over in the house, we can mount the sensors on robots. Robots are mobile and can be customized for handling different tasks. This idea is the basis of our larger research project, Multimodal Elderly Care System (MECS), but let us first examine what other projects have done.

A. Other Projects Looking at Elderly and Robots

Several robots have been built to help the elderly. One example is Care-o-bot [8], [9] that can assist in multiple tasks for the elderly at home. The Paro seal robot has been used to look at how elderly and people with dementia react to a robot in a nursing home context [10]–[12]. Others have investigated how the elderly interact with robots. One study looked at a robot that interacted with the elderly in social situations and during card games [13].

The European Commission has financed several projects that investigate the elderly and robotics. The Acceptable robotiCs COMPanions for AgeiNg Years (ACCOMPANY) project modified the Care-o-bot to provide emotional and social support for the elderly [14]. ACCOMPANY also examined viewpoints of what the robot should do when the older people disobey the robot's recommendations [15]. The Managing Active and healthy aging with use of caRing servIce rObots (MARIO) project used a service robot to help address the issues of the elderly's feelings of loneliness, isolation, and dementia [16]. The Giraff robot was used in multiple projects. In the Enabling SoCial Interaction Through Embodiment (ExCITE) project, the Giraff robot was used for telepresence of other family members in the elderly's home [17], and in the GiraffPlus project, the Giraff robot was upgraded to include monitoring [18].

A recent review of healthcare robotics pointed out that robots can fill gaps and help overloaded care workers, but that there is no one-size-fits-all solution to most health issues [19]. If robots shall succeed, different groups need to work together. From asking the elderly, a survey found the elderly wanted help for specific things like recovering from a fall and fetching and reaching objects [20]. However, a report on the progress of robots for use in helping elderly live independently found that current robots must provide more help and services if they will truly aid people to live independently longer at home; these robots must be more than a tablet on wheels [21].

These are all points that we consider when we are working with robots in the home of the elderly in the MECS project. In addition, we have also sought the advice and cooperation of members from some of these previous projects.

B. The MECS Project

We are investigating collaboration between human and robots in the Multimodal Elderly Care Systems (MECS) project. This multidisciplinary project is funded by the Research Council of Norway and is examining helping the elderly at home by offering safety alarm functionality in a robot. The project investigates algorithms and sensor data to help predict abnormal behavior by checking the presence of the person at home, checking the person's breathing, or noticing if someone is unstable and may fall soon.

We are concerned that the elderly do not feel that they are under constant surveillance. We are investigating data protection issues and having the robot using privacy-preserving sensors like thermal sensors [7] or ultra wide-band sensors [22]. A robot at home may let the person feel in control and give the person some privacy. For example, an elderly person could tell the robot to leave the room so the person could be alone.

Robots cannot replace a human in every context, but they can provide support for issues when a person cannot be present or contact a person for assistance. The robot can also assist by taking over tasks of drudgery. This allows visitors more meaningful interaction with the residents in the home. Robots may help in ways that would otherwise require another human to always be present and have diverse knowledge. For example, robots can collect data and use algorithms to give early warnings about issues (e.g., falling down, low blood pressure, or suffering from poor nutrition).

In MECS, we work with Kampen *Omsorg+*, a program in the City of Oslo that aims at helping elderly people live longer at home. Kampen *Omsorg+* provides modern apartments with common areas for residents to socialize. Currently, most residents have a Scandinavian background. This setting provides a good context for understanding the residents' needs, designing robots and sensors that can be helpful for the residents, and evaluate these robots and sensors over a long-term period in the residents' apartments.

Having a robot at home means that the residents will have to interact with the robot. To aid in observation, the robot will move between the rooms and with people. One of the areas we are investigating is how we can have the robot move in the home and improve interactions between residents—the elderly—and the robots.

III. Movement, Animation, and Style

It is important to define terms related to this phenomenon. This section examines *movement*, *animation*, and *style*.

A. Global and Local Movement

Physical movement (or motion) is a change in position over time. We call this *global movement* (Figure 1a). If we were to imagine the robot in a house, global movement would mean the robot moves in a room or moves to another room. *Local movement* is when parts of a robot move, but its global position does not change—for example, a robot at rest and waving at a person (Figure 1b). For simplicity, we will also define when no parts of the robot move and no change in global position as a special case of local movement. Of course, local movement and global movement can be combined.

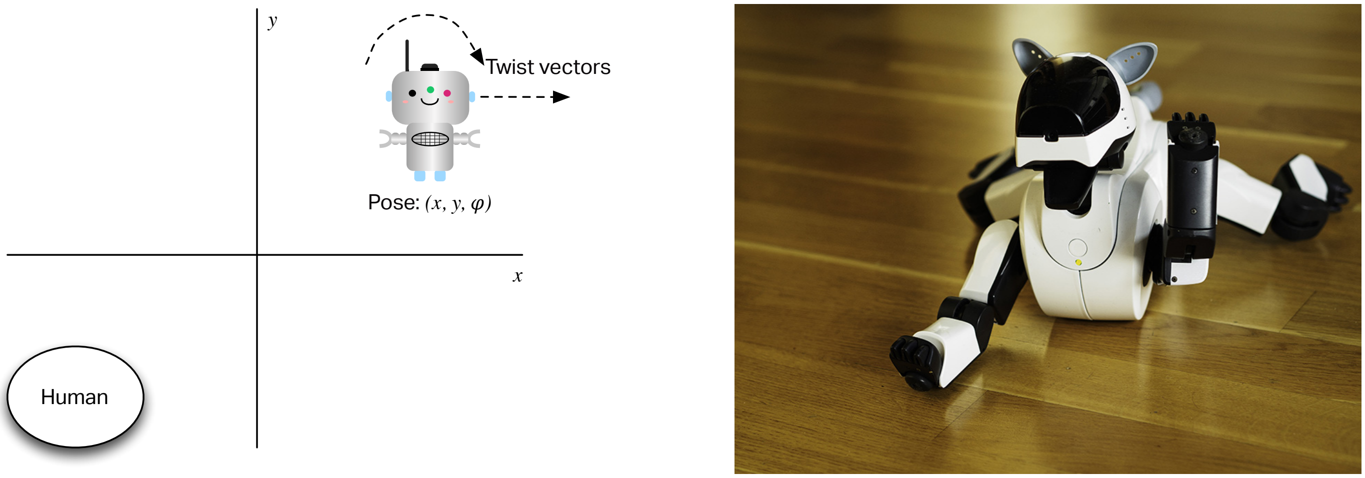
B. Animation and Style in HRI

There are many ways a robot can move. The robot can move at a constant speed, speed up quickly as it starts out, and slow gradually down when it reaches its destination. Or it can reverse to gather a running start or brake abruptly to signal its arrival. All of these different movements can be programmed.

In movie animation, animators use software, pencils, or pens to "program" the movement of their objects on a screen. So, one could argue a robot's movement could be animated. However, if animation was solely movement, then any movement would be animation. For *animation*, it is *not* the movement itself we are interested in, but *how the movement is done* and *how the movement is perceived* by the people interacting with the robot. Animation in movies shares these concerns. Some animation appears to audiences as smooth and believable, while other animation appears to the audience as jerky, quickly-assembled, and not believable. This implies some craft is necessary.

So, animation in HRI has two parts. The first part is using techniques from animation in movies or computer graphics (or inspiration from them) to specify how a robot moves. The second part of animation and HRI is the human side. How is this animation perceived by the humans that are interacting with the robot? If there is no HRI, then there is little reason to do the animation and instead optimize movement for other factors such as maximizing or conserving power.

We posit that animation can improve people's interaction with a robot. One way to improve the interaction is by using animation techniques to give the robot *style*. Style in this context means the way "a behavior is performed" [23, p. 133]. Style can also be thought of as *expressive movement*. Gallaher looked at people's style, and this concept has been successfully applied to robots [24], [25]. Animation gives the robot an interesting way of moving, a style. This animated motion can make the robot seem like it has a personality. The motion can also help the robot to better communicate what it is planning to do.



(a) (b)

Figure 1. Examples of global and local movement: in global movement (a), the robot moves in a two-dimensional plane; the Aibo laying down and waving (b) is an example of local robot movement.

C. Principles of Animation in Previous HRI Studies

Thomas and Johnston [26] documented twelve principles of animation that animators at Disney used to create their animations. These principles include: (*a*) *squash and stretch*—an animated object squashes and stretches its form, but never truly loses its recognizable shape; (*b*) *anticipated action*—an object needs to prepare itself before performing an action; (*c*) *follow through and overlapping action*—actions are not done in isolation, characters move seamlessly between them; (*d*) *arcs*—limbs move in arcs, not straight up-down, left-right motions; (*e*) *secondary action*—the object's main action causes other secondary actions to occur at the same time; (*f*) *exaggeration*—over-emphasizing an action helps people understand a characters feelings; and (*g*) *slow in, slow out*—the speed of motion is not the same the entire time, but slower at the beginning and the end.

Previous work in HRI has adopted some of these principles when creating robots. The principles were referenced when creating the movement and emotional reactions for the Kismet robot [27]. This made Kismet's reactions easily recognized by participants in the study. Van Breemen [28] advocated to use these principles for robots, and he applied some of them to make facial expressions of the iCat more natural and less machine-like [29].

Animation can make things "look alive" or give them *animacy*. This can cause people to treat the robots as if they were alive. For example, in several experiments, participants worked with an animated robot for a while. Then, the participants were asked to destroy the robot by turning off its power to erase its memory [30],[31]. The animated nature of the robot and its perceived intelligence made some participants hesitate to destroy the robot.

Applying animation principles has aided participants' interaction with a robot in several other studies. For example, animation principles can make it easier for a human to understand and predict what a robot is doing [32]. Using the principle of anticipated action made it easier for participants to predict what the robot was going to do [33]. Another example is using the principle of exaggeration on a robot telling stories. The robot's exaggerated motion resulted in participants remembering those specific parts of the story better [34].

So, using animation principles with robots has changed people's interaction with the robots. To examine this in the home environment, let us classify a human's and robot's movement in the home and see how this relates to other types of movements. Then, we can see how animation techniques can be applied to make robots' movements more familiar and provide a possible implementation of the animation principle of slow in, slow out.

IV. Classifying Human and Robot Movement

Traditionally, human-computer interaction (HCI) was the study of the use, design, and evaluation of people interacting with interfaces in different contexts such as stationary computers in workplace settings, public places, and home settings. Mobile computing raised the importance of the context of use and interaction to researchers' attention. This lead to the research area of *context aware computing* [35]. Ubiquitous and ambient computing raise the idea of computers in the home, but hidden from view and not moving.

The conditions for the interaction taking place between humans and computers in a stationary and mobile situation are similar; there is a stable spatial arrangement between the people and computers. In both situations, humans and computers are interacting in the same place, with a stationary relationship in-between the humans and the computers.

The spatial conditions change when robots enter the scene. We may be used to moving things outside our home like automobiles, buses, boats and trams. But in a home setting, we are not familiar with *things* moving around *on their own*.

In the home context, we can classify this movement: (*a*) Things that we move around: furniture, peripherals, clothes, machines like vacuum cleaners or furniture on wheels. (*b*) Things moving themselves: domestic robots (robot vacuum cleaners and robot lawn mowers) and other types of robots.

If we examine the spatial arrangement for movement between one human and one robot and classify the movement as *local* and *global* from Section III, we find the following four conditions (Table I):

1) Human moves locally and the robot moves locally,
2) Human moves locally and the robot moves globally,
3) Human moves globally and the robot moves locally, and
4) Human moving globally and the robot moving globally.

TABLE I. MOVEMENT CONDITIONS FOR HUMANS AND ROBOTS

Condition	Human	Robot
1	Local	Local
2	Local	Global
3	Global	Local
4	Global	Global

This framework for classification also gives a way to compare the human-robot movement with other objects. In Condition 1 and Condition 3, when the robot is moving locally (including being completely still), the human is either moving locally or globally. This is similar to conditions for interacting with stationary computers. We can see Condition 1 when a person watches TV, and we can see Condition 3 when a person approaches a switch or walks towards a remote control.

The other conditions are more unusual in the home before robots. For example, Condition 2 happens when toys are moving. But Condition 4 does not have good analogs other than perhaps chasing a moving toy. These other conditions also indicate something that is unfamiliar. Gibson and Ingold [36] find we are indeed familiar with movement, and they work out the importance of movement on perception. Let us investigate the phenomenon of familiarity and how moving robots in the home might become more familiar to the elderly at home.

V. FAMILIARITY AND MOVING ROBOTS AT HOME

We can examine the phenomenon of familiarity using phenomenology; that is we look at how people experience what is familiar and unfamiliar. Once we have an idea what familiarity is to humans, we can look at how we can make a robot's movement familiar. We can also see how animation and style can help in making these situations familiar.

A. Familiarity

Familiarity plays a role in how people interact and use things and objects. The familiar is often what we are comfortable and safe with, be it situations, technologies, relationships, activities or other people. We are often unfamiliar with things we do not engage with, things we do not understand, or things that are foreign to us.

These three concepts; *involvement*, *understanding*, and *unity of user-world* are, according to Turner and Walle [37], ideas that we can apply to understand familiarity. Turner and Walle stated that familiarity unfolds over time. Hence, familiarity points to activities of daily living where we are engaged and skillful people going about our everyday lives. When breakdowns or interruptions happen—for example, something is faulty, missing or in our way for us to proceed—the separation between people and their world is taking place, and equipment and activities become visible as objects for our analysis [38]. However, this is not the primordial way of being in the world.

Van de Walle, Turner, and Davenport claimed, "What is observable are the outcomes: easiness, confidence, success, performance, which are all manifestations or signs of familiarity," [39, p. 467]. This shows that familiarity is subjective; it can be described by observing activities or asked questions in interviews. One way of investigating possible ways of using robots in the home is to learn from what we already are familiar with of movement. Harrigan, Rosenthal, and Scherer [40] provided an introduction into non-verbal human behavior, including *proxemics*. Hall [3] observed that human-social spatial distances vary by the degree of familiarity between the people interacting and the number of people interacting. Hall later provided a framework that identifies the main social spatial zones by interaction and situations. He estimated these distances visually in terms of arms lengths, close contact and threat/flight distances—and researchers have since assigned precise numerical values.

B. Making a robot's movement more familiar

As Gibson and Ingold [36] claimed, we are all familiar with movement. Moving within a place, such as a home, is an example of movement that we all experience daily. We are familiar with seeing other people move. We are familiar with seeing things move. We move about in concert with things such as phones, watches, and footwear. There is nothing extraordinary with this familiarity of movement of things and other people. By focusing on the familiarity of movement, we build on people's preexisting involvement, understanding and relationship with the everyday world.

The concept of *human-to-human* proxemics has human-human movement at its base and has been used when designing interactions with robots [41]. This use of human-human proxemics has been developed further to take the context of the activity and the person's location into account in how the robot should approach the person [42]. All of this is dependent on people wanting to interact with a robot as though the robot was a human. Some people assume that robots are simply things and approach a robot much closer than they would another person [41]. So, depending on how people will interact with the robot, another possibility may be to use *human-thing* distances and proxemics as the starting point instead of human-human proxemics. This would be grounded in our familiarity with the movement of things.

If we think of familiar movement where an object moves with us, we can find some examples: (*a*) navigating traffic, with cars, bicycle and public transport material, (*b*) walking with a rolling suitcase, (*c*) operating a wheelchair, (*d*) operating a walking stick, and (*e*) operating a walker. We are all familiar with doing or observing such movements, but there is no distinct research field literature to find out more about these types of movement. However, the concept of familiarity helps us find these examples.

C. Making a robot more familiar by giving it style

In Section III, we posited that an animated robot moves with style. Several of the robots from Section III do not move from their location, but the way they move their parts makes them appear more friendly and easier to relate to. Animation also makes it possible to experiment with different kinds of interaction depending on the animation style.

In HCI and graphical user interfaces, programmers can move items across the screen in many ways, and animating user interface elements can help people understand what is going on when they are using a program [43]. There is a different mood or tone when a window minimizes by shrinking down to a small area on the screen versus simply scaling the window [44]. Just as animated graphical user interface elements help explain what is going on, the way a robot moves can be helpful in explaining what is going on in an interaction with a robot. Naturally, there are limitations—for example, robots must obey the laws of physics and some types of motion put extra strain on the robot [45]—but we can give a robot its own style by animating it.

Animation can be present in all conditions in Section IV. For example, in Condition 1, the robot does not move globally, but its local movement can still be animated by moving parts of its body. This animation can give the robot a style, add some personality, and give the effect of presence for the robot [46]. For example, if the person is asking a question or the robot is providing feedback, animation can provide feedback to the person about the robot's state and other relevant information. This does not have to be complex; a part of the robot rotating can suffice, or lights blinking to indicate the robot is listening. A simple rotation that follows the person can help keep the interaction going in Condition 3.

Condition 2 can build on the animation from Condition 1. Here, animating parts of the robot's body can be combined with its global movement. For example, if the person asks for some privacy, the robot can start moving away. This can give the person a sense of what the robot is going to do. Using animation techniques could also affect how fast the robot moves, combining several animations techniques could make a robot "appear" angry, sad, surprised, or happy.

Since these two conditions can build on each other, animation techniques can also help with the *transition* between them. This can offer the human a cue to the robot's intention. From the robot's side, it can also try to determine the human's cue to get information if it too should start or stop.

Condition 4 is still unfamiliar for most indoor settings. Animating the robot's movements can give it a style to make it seem like this condition is more familiar. The way the robot moves can imitate another person or an animal. These imitations can remind us of other situations where we and something else move, and this can make a robot and human moving at the same time more familiar.

There is familiarity in motion and there is familiarity in *forms*. Hoffman and Ju [47] posit that robots that resemble something we are familiar with may bring assumptions and expectations that are difficult to achieve given current technology. Instead, a robot that does *not* resemble a human or animal can move expressively to provide clues for interaction. These movements follow physical properties in the world that people are already familiar with and give them a starting point for their interaction.

Returning to proxemics, animation techniques can aid in building rapport between robot and human. One study has found that rapport is necessary for people to be willing to get physically near to a robot or answer personal questions [48]; until a rapport is established, certain actions that signal a good rapport (like maintaining eye contact) should be avoided. A different study found different distances for an approaching robot based on the posture of the human (sitting or standing) [49].

This framework for investigating movement gives insight in how to give this movement style through animation techniques. The way these movements are animated may influence how willing someone is to interact with it. A previous study found the speed and way a robot moved caused people to describe the personality or mood of the robot [50]. Building on this work, Another study found people associated negative and positive emotion to a simple robot simply by adjusting how it accelerated [51]. A proper balance needs to be found. For example, a robot moving too fast may prove frightening, and if a robot moves too slow, people may assume that the robot can never get anything done. If we desire interaction with a robot that moves, we need to make it an inviting experience. This is where using animation principles like slow in, slow out (Section III-C) may better mimic familiar movement of other objects. Let us explore how this can be done.

VI. Using the Principle of Slow In, Slow Out on a Robot

Having explored robots' movement and familiarity by using the theory of phenomenology, we discuss how to make a robot move following the animation principle of slow in, slow out. This focuses on global movement, but it can be applied to local movement as well. First, we start by describing robot motion formally and the robot's generic *velocity profile*. Then, we derive a new velocity profile based on the slow in, slow out principle. Finally, we discuss how this works for robots in the real world.

A. Poses, Twists, and the Velocity Profile

Robot motion is described in terms of *poses* and *twists* [52] (Figure 1a). A *pose* provides the position and orientation of the robot. If we are on a two-dimensional plane, a pose is normally recorded as a tuple (x, y, ψ) where (x, y) is the position of the robot in a room, and (ψ) is the robot's orientation, i.e., which direction the robot is facing. A *twist* provides information about the different velocities the robot is traveling. For a robot that moves on the ground, these velocities are the *angular* velocity—the velocity that the robot is turning and the *linear* velocity—the velocity in a line.

When a robot moves, it has a *velocity profile*. A velocity profile is a graph of the robot's velocity versus the distance that it travels. If we assume a robot moving in a straight line in ideal, non-friction conditions, the idealized velocity profile looks like a trapezoid (Figure 2a). The robot accelerating from a velocity of zero to its cruising velocity makes one of the diagonal lines (a_{RampUp}). The constant cruising velocity (v_{Cruise}) forms a parallel line with the distance axis. Finally, the robot's deceleration down to zero as it nears its final location forms the other diagonal ($a_{RampDown}$).

There is also a special case when the distance to travel is shorter than the distance needed to reach the robot's cruising speed. The robot accelerates up to a speed (v_{Peak}), but then slows down as it approaches its final spot. This case results in a triangle velocity profile where acceleration and deceleration form the legs of the triangle (Figure 2b).

We can formalize the different parts of these variables in terms of time (t), distance (d), and the different velocities (v).

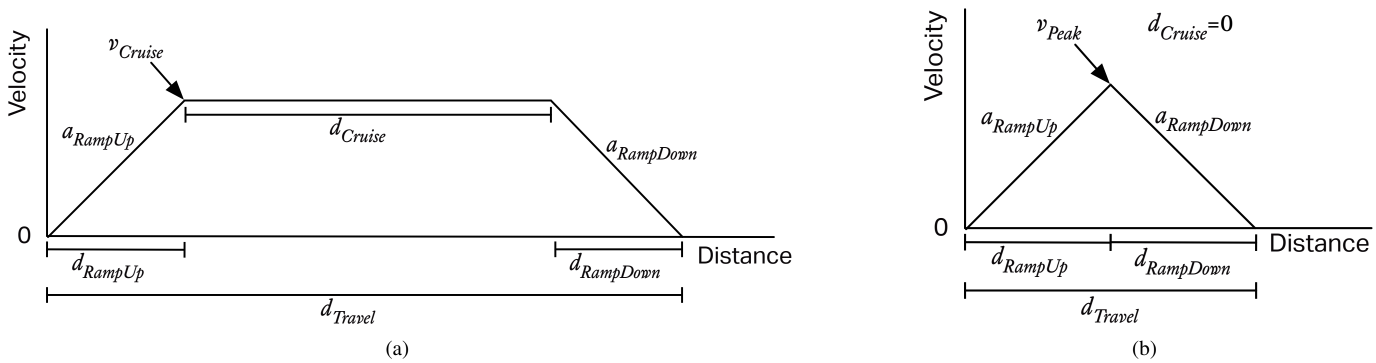


Figure 2. Examples of velocity profiles, a plot of velocity over distance. (a) The trapezoid profile is normally used for long distance movement. (b) The triangle profile is a special case of the trapezoid when the cruising distance is zero (adapted from Newman [52]).

$$d_{Cruise} = d_{Travel} - d_{RampUp} - d_{RampDown}$$

The cruising distance (d_{Cruise}) is the total distance traveled (d_{Travel}) minus the distance traveled during ramp up (d_{RampUp}) and ramp down ($d_{RampDown}$).

$$\Delta t_{Cruise} = \frac{d_{Cruise}}{v_{Cruise}}$$

The time spent at cruising speed (v_{Cruise}) is the cruising distance (d_{Cruise}) divided by v_{Cruise}.

$$\Delta t_{RampUp} = \frac{v_{Cruise}}{a_{RampUp}}$$

The time spent in the ramp up (Δt_{RampUp}) is the cruising speed (v_{Cruise}) divided by the acceleration at ramp up (a_{RampUp}).

$$\Delta t_{RampDown} = \frac{v_{Cruise}}{a_{RampDown}}$$

Similarly, the time spent in the ramp down ($\Delta t_{RampDown}$) is the cruising speed (v_{Cruise}) divided by the acceleration at ramp down ($a_{RampDown}$).

$$\Delta t_{Move} = \Delta t_{RampUp} + \Delta t_{Cruise} + \Delta t_{RampDown}$$

The time spent in movement (Δt_{Move}) is the sum of the time spent in ramp up (Δt_{RampUp}), the time cruising (Δt_{Cruise}), and the time spent in ramp down ($\Delta t_{RampDown}$). All of these equations allow us to define a distance function (Equation (1)).

$$d(t) = \begin{cases} \frac{1}{2} a_{RampUp} (t - t_0)^2, \text{for } 0 \leq t - t_0 \leq \Delta t_{RampUp} \\ d_{RampUp} + v_{Cruise}(t - \Delta t_{RampUp}), \text{for } \Delta t_{RampUp} \leq t - t_0 < \Delta t_{RampUp} + \Delta t_{Cruise} \\ d_{Travel} - \frac{1}{2} |a_{RampDown}| (\Delta t_{Move} - (t - t_0))^2, \text{for } \Delta t_{RampUp} + \Delta t_{Cruise} \leq t - t_0 \leq \Delta t_{Move} \end{cases} \quad (1)$$

The velocity profile implies that the acceleration is *constant*; that is, the velocity changes at a constant rate until it reaches the maximum speed. This constant acceleration and speed gives us the mechanical movement that we associate with a robot. If we change the acceleration and the speed, we may be able to apply some principles from animation with the robot's motion.

B. Deriving Slow In, Slow Out for the Robot's Movement

When animating something in movies or in computer graphics, the movement of the object is controlled by drawing the object at a certain position for each frame that is shown on the screen. This gives the animator a great deal of control in the speed of the object. For example, if an animator changes the position only a small amount for each frame, the object will appear to move slow. The reverse is also true, a large change in position of an object between frames creates a fast moving object. If an animator wants to use the slow in, slow out principle, both of these techniques must be used.

A programmatic way to accomplish the movement is to use an *easing curve* (example curve in Figure 3). An easing curve specifies a time-distance curve that goes from zero to one for both the time and the distance. This way the animator needs to know only the starting point for the movement, the end point for the movement, and the total time to complete the movement to plot the animation.

Then, for each frame of animation, the animator calculates the frame's time as a percentage of the total time to complete the movement and finds out the percentage of the distance that should be complete. This technique is easy to automate, but requires someone to decide the initial inputs. An additional advantage is that different easing curves will create different effects. For example, an easing curve that goes over then under the distance of 1.0 before ending at 1.0 will appear to "bounce around" its end point before stopping.

The slow in, slow out animation principle states that an object should slow speed up to its top speed and then quickly slow down as it arrives at its final location. The slow in can be simulated by a curve like t^3 and the slow out can be simulated by the negative version $(t-1)^3+1$. To combine them together into one curve that goes from zero to one, the equation is:

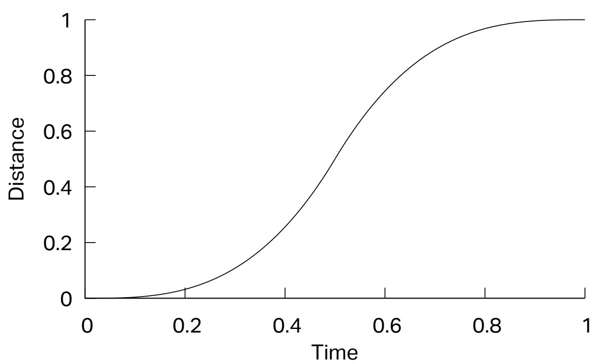


Figure 3. Easing curve for a cubic growth for the first half of the journey and cubic decline for the second half (Equation 2).

$$d(t) = \begin{cases} \frac{(2t)^3}{2} & \text{for } 0 \leq t \leq 0.5 \\ \frac{(2t-2)^3+2}{2} & \text{for } 0.5 < t \leq 1.0 \end{cases} \quad (2)$$

The graph would look like Figure 3. (2) is noticeably different than (1), but (2) does not have to take into consideration acceleration.

This works fine when an animator sets the position of an object on a screen and worries only about how often a frame is shown. For robots, there are physical limitations such as how fast parts of the robot can move, friction, and inaccuracies of sensors and actuators. Rather than setting the position directly, the robot controls its acceleration or velocity, which are complementing ways of expressing motion.

From calculus, we know that the derivative of a distance function is a velocity function. This means that we can find the velocity at any point in time by taking the derivative of Equation (2). The derivative (graph in Figure 4) is:

$$v(t) = d'(t) = \begin{cases} 12t^2 & \text{for } 0 \leq t \leq 0.5 \\ 12t^2 - 24t + 12 & \text{for } 0.5 < t \leq 1.0 \end{cases} \quad (3)$$

Equation (3) gives us slow in, slow out movement for short travel conditions. The curve does not go from zero to one (it goes from zero to three), but, as Equation (2) gives the position for a specific point in time, Equation (3) can be scaled to give us the velocity we need at a certain point in Δt_{RampUp} and $\Delta t_{RampDown}$. With no cruising velocity in Equation (3)—the curves up and down of Figure 4 resemble the straight lines of Figure 2b.

Since the triangle velocity profile is a special case of a trapezoid velocity profile, we can create a similar version for the trapezoid case. Conceptually, to make this profile similar to Figure 2a, the speeding up and slowing down should be split at $t = 0.5$, and the cruising speed should be put in between the split. Formally, it makes sense to divide things up into three parts. During Δt_{RampUp}, a quadratic curve is used to accelerate the robot. During Δt_{Cruise}, the robot maintains its cruising speed. Finally, during $\Delta t_{RampDown}$, a reverse quadratic curve is used.

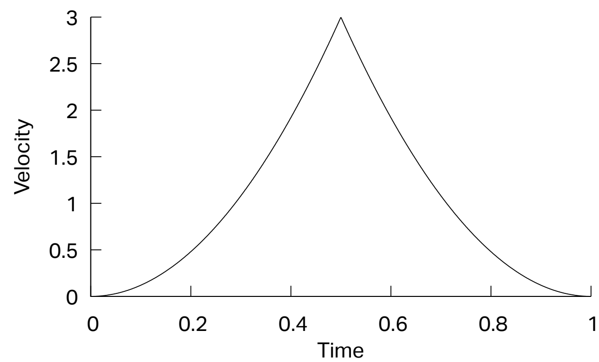


Figure 4. The derivative of the easing curve shown in Equation 3.

C. Implementing Slow In, Slow Out on a Robot

We implemented this algorithm for use with the "Burger" variant of TurtleBot3 (Figure 5). TurtleBot3 is a research robot from the Open Source Robotics Foundation [53]. The Burger variant has two wheels driven by servos and a ball bearing to keep its balance. Using the servos, the robot can go forward, backward, and turn itself around using skid-steer techniques.

The algorithm is a C++ node for the Robot Operating System (ROS) [54]. ROS functions as middleware where different nodes communicate by publishing and subscribing to different *topics*, such as twist commands. These nodes can be located on any machine or robot in the network. In this case, we are publishing twist commands about the angular and linear velocity the robot should be running on a topic called `cmd_vel`. The TurtleBot3 subscribes to the topic and adjusts the speed of the servos accordingly.

The node works by taking parameters for going forward and turning. For moving forward the distance to be traveled (d_{Travel}), the top speed of the robot (v_{Cruise}), and the time it takes to accelerate to achieve the top speed (Δt_{RampUp}) can be adjusted. Once the parameters are set, the node publishes twist commands periodically until the motion is complete. During the ramp up time, the node publishes twist commands that follow the curve $3t^2$. Once the robot reaches its cruising speed, the node publishes twist commands at the cruising speed until it is time to start slowing down. Then, it publishes twist commands that follow the curve $3(t-1)^2$ until the ramp down is completed. With the robot at its final destination, the node publishes a twist command with no angular or linear velocity to ensure the robot is stopped. For distances that are under the maximum velocity, the node finds a $VPeak$ by recursively reducing speed until it can create a curve that can accommodate the distance.

For turning, the parameters are: the number of degrees to turn (positive for left, negative for right) and the time to use on turning. The node then publishes commands for speeding up and slowing the robot according to Equation (3). Like the linear motion, it also publishes a twist command with no angular or linear velocity to stop the robot once the turn is complete.

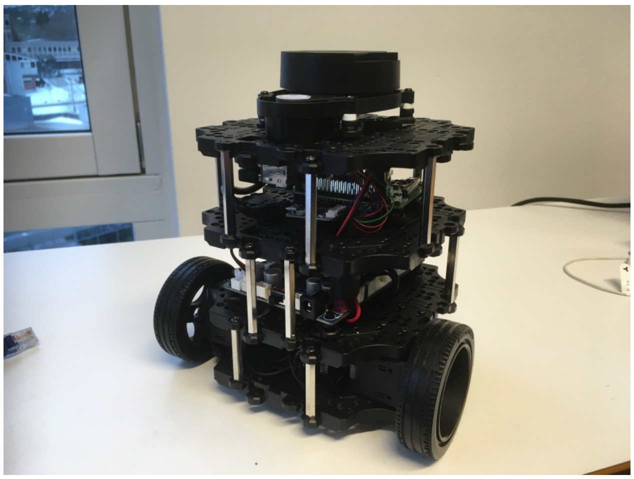


Figure 5. The TurtleBot3 “Burger” model that was used for testing slow in, slow out motion.

This node was tested against a simulation of a TurtleBot3 Burger robot. This was done with the “fake node” (a node that responds to the same messages as the real robot) and the Gazebo simulator (a simulator that includes gravity and friction). In both cases, the simulations of the robot show a difference between the regular constant movement and slow in, slow out movement.

Moving from a simulated TurtleBot3 robot in a simulated world to an actual TurtleBot3 in the real world revealed some limitations. First, the speed of the servos in the real-world are limited to 0.22 meters per second (m/s); that speed is much less than most people walking. However, this is only really an issue if you ask for a speed higher than 0.22 m/s. In those cases, an acceleration curve was generated for the requested velocity, but acceleration stopped once the TurtleBot3 reach its maximum speed and you would not see slow in, slow out movement. Regardless, even when using the correct speed the difference in the linear and slow in, slow out movement is visible, but less pronounced.

To see if this is an issue with physics in the real world or just the difference in speed, we have since tried the movement with a robot, a Fetch Robot (Figure 6), that can move at 1 m/s. This results in a visible difference in how the robot speeds up and slows down when using slow in, slow out and linear acceleration.

Another issue to explore is the number of times per second the node should publish new speeds. Originally, this was done 30 times per second. This works fine in a simulator, where the updates happen nearly instantaneously. In the real world, there is a small delay between broadcasting the signal, to receiving the command, and telling the servos to change speed. The result is that it is hard to know how many twist commands are actually processed by the TurtleBot3. Sending less commands, for example 20 times, 15 times, or even as low as five times per second still results in a noticeable change in the robot’s movement.

Figure 6. The Fetch Robot navigation stack was modified to provide slow in, slow out movement.

This node blindly sends out its twist commands. So, a mistakenly calculated distance may have the robot crash into a wall, fall off a table, or worse. A robot in the real world needs to be aware of its environment, and this node must be integrated into the navigation system. This means that the robot uses slow in, slow out to move while also being aware of obstacles and finding its own way to a destination. We have a preliminary plugin that can be used by the Fetch robot’s navigation code. This makes it possible to run evaluations of the different ways of movement with people interacting with the robot in a home environment.

VII. Future Work

There are limitations with movement classification from Section IV, since it only looks at a specific case of one human and one robot. There are opportunities to explore different directions of movement as well. However, even at its simple level, it gives us many questions we can investigate: how can the robot move to bring trust and assurance when the person is interacting with the robot? What activities can a robot do that are not available when a technology is stationary or handheld? What conditions are necessary so that people and robots can collaborate together? How are these interactions affected by the animation, proximity, automation, control, and delegation? We can also examine the transition between the different classifications.

Moving with style can be helpful. However, different people prefer different styles, and some styles may work better in some situations than others. Finding styles that are compatible with the robot, the people, and the situation will be a challenge.

Another issue is how the animation can be tested. Many of the animation studies that we cited in Section III were run in lab situations. This works well for testing items in a controlled environment, but robots at home need to work in dynamic environments. Testing the animations out in a home environment may be necessary to see if the animation is helpful for the elderly.

We did not examine who controls the robot in the home situation. From our discussions in gathering requirements from the elderly, people have different opinions about a robot moving at home when they have control of its movement versus it moving on its own. There is also a question about what control means in a home situation with the elderly. In Section II-B, we highlighted the idea of the elderly asking the robot to leave, but there are also situations when the robot should stay or come back quickly to join the elderly person autonomously.

As Chanseau, Lohan, and Aylett [55] found, people who wanted a feeling of control also wanted robots to be more autonomous. The size of the robot and a person's anxiety towards robots also influences proxemics. These issues are important when introducing a robot—especially moving robots—in the home of the elderly. Introducing a robot that can detect falls benefits no one if it moves around the home and becomes an obstacle to stumble over in everyday life. Then, it is a fall *creator* for the elderly instead of a fall *detector*.

The movement classification could be expanded and applied in other areas. Are there other situations outside of home where this classification applies as well? What happens when you add more "moving parts" like other people and robots? Does animating a robot work in all situations? What about animating robots that have limited movement? These are all questions to explore in future research.

As to the implementation of the slow in, slow out movement, since a robot using the implementation can now navigate in an area with humans, we are working on creating an experiment in the home context where people interact with a the robot and it moves using either a regular linear velocity curve or a slow in, slow out velocity curve. Our goal is to see how slow in, slow out velocity curves affect participants perceptions of the robot. Preparations for this experiment are underway and we hope to begin gathering data in the near future. If they are successful, we hope to repeat the experiment in other contexts or other robots to see if the slow in, slow out principle can be applied in multiple cases.

VIII. Conclusion

We investigated robot movement in the home and classified the movement in relation to humans and their movements. We have used the phenomenon of familiarity to link familiar movement outside the home with the unfamiliar movement of a robot inside the home. We also suggested that animating the robot will make it move with a distinctive style. This style can give to the robot a personality and make the robot more familiar to people living at home.

Further, we showed how we could apply one of the principles of animation (slow in, slow out) to a robot. We accomplished this by taking an easing curve from computer animation and deriving a formula that would be useful to a robot that can control its speed. This formula has been implemented as an algorithm in a node in ROS and tested both in simulation and in the real world with a TurtleBot3.

We are working with the elderly by running focus groups and discussing the issues of robots at home and how a robot's appearance and movement affects them. The information and the elderly's opinions have been helpful, and they seem interested in what things robots can do. We will be presenting this in future work and are integrating their feedback into our future activities. We will also be using the results from future experiments in our implementation to see how animation techniques can give the robot a distinctive way of moving.

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