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Human robot interaction in the absence of visual and aural feedback: Exploring the haptic sense

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Abstract

The potential of robot swarms for Search and Rescue has been shown by the Guardians project (EU, 2006-2010); however the project also showed the problem of human robot interaction in smoky (non-visibility) and noisy conditions. The REINS project (UK, 2011-2015) focused on human robot interaction in such conditions. This paper briefly reviews the scientific context relevant for designing a haptic interface for human robot navigation and examines what we have achieved since then. The aim is to put the major design issues into context.

Keywords: Haptic Human Robot Interaction, USAR.

1 Introduction

The Guardians project[*] (EU, 2006-2010) showed the potential of robot swarms for Search and Rescue; however the project also showed the problem of human robot interaction in the absence of visual and aural feedback. The Reins project[†] (EPSRC, 2011-2015) focussed on this problem and studied the contextual basis of tactile and haptic human robot interaction in low visibility conditions. The project applied a tangible physical connection to link the human and the robot. Visual and aural feedback were excluded from the interaction; the aim was to explore the interaction landscape emerging in a human-robot team by using a physical connection only.

Current navigation aids mostly rely on the visual sense or verbal information. The haptic sense is largely overlooked despite it being extraordinary fast. The future outlook of our project is to create the appropriate equipment with which a human and a semi-autonomous robot would be able navigate in sensory-deprived conditions. The latter is still unsolved and remains an open problem.

We note that different senses convey information in different neural circuits. Even though we are not in a position to report great practical successes with haptics on its own, we believe there is enough ground to continue investigating. In future applications the haptic sense may complement the visual sense and it has potential to enhance spatial awareness via its particular neural route.

The current paper briefly reviews aspects from the very diverse scientific context that are relevant for designing a haptic interface for human robot navigation. The aim is to assess our experiences and to put the major design issues into context.

[*] Guardians, IST 045269, refer to http://www.guardians-project.eu/

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2 Real life situations

2.1 Search and rescue

Search and rescue operations are often undertaken in zero-visibility and noisy conditions; smoke, usually thick black smoke, hampers sight while the breathing apparatus and the fire create a lot of noise. Smoke causes huge problems for human beings, but also for robots navigating in smoke is not trivial. Smoke, mist and dust present a challenge to the conventional (visual light based) sensors used in robotics. However, alternative sensor technologies are available to enable robots to explore these difficult environments.

The Guardians project (Penders et al., 2011) succeeded in providing a proof of concept for a group of robots to navigate in smoke and maintain a group formation while accompanying a human fire fighter. However, guiding a fire fighter turned out to be problematic. For feedback from the robots to the human firefighter, a light array was built into a fire fighting helmet. The array depicted directions, with the vertical axis associated with the straight forward direction while the horizontal axis corresponded with the left right directions. Following comments from professional fire fighters at a first trial, the direction indicator was simplified and limited to the basic angles -90^0, -45^0, 0^0, 45^0 and 90^0. In operation, illuminated LEDs indicated the safe direction.

The usual operational procedure for fire fighters using breathing apparatus is to keep close to a wall, touching the wall nearly continuously. The light array was trialled again with fire fighters. When the array indicated a safe direction away from the wall the firefighters did not follow the instruction!

Rescue teams rely heavily on haptic feedback for exploration and -not to forget- safe exit. Apparently, the firefighters in our trial were not prepared to give up the reassurance provided by touching the wall and become fully dependant on the light array. We concluded that a rethinking of the human interface, taking into account haptics would be necessary. However, in the literature little attention has been paid specifically to haptic sensitivity in such contexts or to the potential of the haptic sense for interactive way finding using robotics devices.

2.2 Visually Impaired Persons

When humans lack direct visual or auditory input from the environment, they find themselves in 'empty space'. Visually Impaired Persons have to live with no or reduced visual inputs. It is known that they compensate the lack of visual input for a large part with the registration of environmental noise. For instance Hull (1990) describes the joy of how a rain shower revives his spatial experience of his garden. For him, being visually impaired, the garden usually is just empty space. There is an obvious analogy for the situation firefighters find themselves in. Though they are provided visual and aural (noise) inputs, these inputs do not constitute relevant information about the environment they are in. In contrast, their hand touching the wall does provide direct and relevant input.

2.3 Guide dogs

Many visually impaired persons have developed highly effective navigational partnerships with specially trained guide dogs; refer to Ireson (1991) concerning the training and use of guide dogs. Penders et al. (2013) have studied the partnership between a human agent and a guide dog. The dogs are treated not as mere ‘devices’, the relationship is mutually and jointly exercised and sustained by a reciprocal behavioural confidence.

The guiding link between user and dog is called the handle, and the user is usually referred to as the handler. The handle is attached to a harness on the dog's back and shoulders. The dogs are trained to work according to a strict protocol: they will lead the handler at a comfortable pace in a (roughly) straight line, in the middle of the pavement. The dog will negotiate minor obstacles on the pavement and make a slight deviation when required; thus, the handler will have avoided an obstacle without knowing it. The handle is not used to push the dog, nor does the dog drag the handler along with it. The default condition is that dog and handler walk at the same pace: the handler feels the dog's movements and direction while the dog monitors the handler's walking and other aspects of behaviour as they proceed together.

The guide dog is not instructed to take the handler to a destination - on the contrary, the handler is taking the dog to a destination. The team is depending on the handler's navigational capabilities. The handler (not the dog) has to find the destination. The dog's role is to provide locomotion guidance, i.e. safe passage between navigational decision points. This activity takes place in locomotor space as it is called in (Ulrich and Borenstein, 2001) and following (Penders et al., 2013) we call the task which the dog performs *locomotion guidance*. Locomotion guidance concerns moving from point to point in a nearly straight line without collisions; and it includes collision avoidance. Locomotion guidance by the dog and navigation decisions taken by the handler are complementary activities, refer to Figure 1.

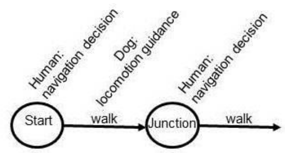

Figure 1, Navigation and locomotion Guidance.

The human-guide dog relationship serves as a paradigm for future human-robot interaction designs, though we emphasise that a human-robot equivalent is still far from being achieved. However, it provided the inspiration for developing a human-robot interface. The interaction consists of mixed initiative and the guide dog does not have full navigation responsibilities. This model seems also appropriate for human-robot interaction and will be used below.

3 Confidence

The key lesson from the Guardians project (Penders et al., 2011) concerning designing a human robot interface is that the human agent must trust and have confidence in the robot guide. The terms 'trust' and 'confidence' are not easy to define. Penders et al. (2013) cite McKinght and Chervany (1996) who define 'Trusting Intention' as follows: 'the extent to which one party is willing to depend on the other party in a given situation with a feeling of relative security, even though negative consequences are possible.' Adding: 'It is personal (originating in a person) and (one-way) directional: one person is willing to depend on the other.' (McKinght and Chervany, 1996). Stormont (2008) notes that while we can usually anticipate the behaviour of our human companions, the unpredictability of an autonomous system is a cause of distrust. Unpredictability undermines the feeling of security and thus undermines trust. Below we focus on enhancing predictability as a very first step to enhance trust for a human robot handler. In line with this, Penders et al. (2013) define Behavioural Confidence as: the extent to which a person believes the current behaviour of another agent is a predictor of (near) future behaviour of the same agent. They belief that confirmed behavioural confidence will result into a trusting intention and reduce reluctance of the human concerning having to depend on the robot.

Below we look at how we can enhance predictability of the robot while the team is operating in no-visibility and noisy conditions. We are not claiming to fully address the issues of trust and confidence, but aim to explore potential requirements for designing a robot and a human robot interface. Obviously the circumstances are such that the interface cannot rely on visual or aural feedback.

4 Handler, Robot and Interface

The interface we are designing has to connect a human handler and a robot. Each can act autonomously and independently; the task is not just to connect them but they will have to adapt to each other in order to collaborate. Adaptation of the robot is a robot design issue, enabling the human to adapt to the robot, while collaborating on specific tasks, is the aim of the interface design.

4.1 Navigation, Locomotion and Exploration

Above we distinguished between the tasks of navigation and locomotion guidance; we use this distinction for the human-robot team as well. Navigation involves way finding and may technically be described as selecting, from the current location, the next waypoint. Locomotion guidance then denotes traversing from the current location to the nearest waypoint.

Figure 2, Firefighters touching the wall on the left, while the other arm and the legs are used to explore.

When exploring an environment in no-visibility conditions, fire fighters use the front foot to stamp ahead, while one hand will be moved up and down in front of the head and upper body; the other hand is touching the wall, refer to Figure 2; they actively explore the 3-D space. Exploration presupposes navigation but in addition requires searching and probing the immediate environment, whether it is for finding a safe passage or for searching to rescue.

In the context of discussing a shopping trolley for the blind, Gharpure and Kulyukin (2008) define the haptic space. The haptic space is the immediate spaces around the person that can be sensed by touch or limb motion without bodily translation. Full support for the exploration of the haptic space is not (yet) our focus: it would require additional actuators on the robots. Below we restrict to a human robot team exploring the floor up to the level of the height of the robot, comparable to the footwork of fire fighters.

4.2 Control and Initiative

The protocol for walking with a guide dog is that the handler remains in control of the navigation. This is also a useful division of labour for the human handler and robot team. Following Stormont (2008) we assume that full autonomy of the robot will not be appreciated by a human subject. However, letting the human control the navigation means that the main initiative in the team remains with the human. (We note that guide dogs are selected partially based on their character: they are not the very dominant characters but rather more docile types.) Therefore, locomotion guidance will be a main contribution for the robot. An additional aim is to apply the robot as an exploration tool. The robot may explore by entering empty spaces or bump into obstacles, for this purpose a 'bumper' will be mounted on the robot, Figure 3 and Figure 6 show pre-prototypes. Exploration will not be exhaustively discussed below; however the points we raise serve to create a context for navigation and locomotion guidance. Locomotion guidance does not provide the person being guided with any information about the environment. Thus, the person being guided is -to use the term form the introduction- guided through empty space. Full exploration of the immediate environment is a future aim; we restrict -as a first step- to investigating how we can provide information of landmarks encountered while the team is proceeding.

4.3 Robot Behaviour for Locomotion Guidance

Guide dogs are trained a strict protocol and they lead the handler at a comfortable pace in a (roughly) straight line, making only slight deviations when required. These deviations generally do not attract attention from the handler.

Important suggestions from this for a robot are that the robot should not move too fast, and in particular should not turn very fast. In a pilot we tried a wall-following robot, partially copying the wall-following behaviour of firefighters. Our improvised wall following algorithm made the robot exactly follow the contour of the wall. However, its moves immediately made the (blindfolded) handler switch attention from following the contour of the wall to wondering what the robot was doing.

We have not extensively investigated the robot parameters; a linear speed of 0.6m/s and an angular speed of 0.5 rad/s (at the turns) are acceptable, though not very fast. Note that these values are below a normal walking speed, usually at a linear speed of 1m/s or more. The ROVI robot discussed by Melvin et al. (2009) moved at 0.2m/s, a speed which we experienced as very slow and thereby making the handler wait for the robot to act.

5 The Haptic sense

As visual and aural feedbacks have been excluded, the interface will have to provide haptic feedback. The haptic sense is relatively under-explored in comparison with sight and hearing; nevertheless it is ‘critical for normal human functioning at many different levels, from controlling the body to perceiving the environment, as well as learning about and interacting with it’ (Robles-De-La-Torre, G. 2006). Research has highlighted the extraordinary speed and sensitivity of the haptic sense (e.g.[12]). Robles-De-La-Torre further notes: ‘In experimental psychology and physiology, the word haptic refers to the ability to experience the environment through active exploration, typically with our hands, as when palpating an object to gauge its shape and material properties. This is commonly called active or haptic touch, in which cutaneous and kinaesthetic capabilities have important roles.’

5.1 Spatial Cognition

How humans represent spatial data in memory is still a subject of ongoing discussions within psychology. A well-known distinction is that between an egocentric representation (a coordinate system centred on the navigator) and an allocentric representation (a coordinate system located and oriented on environmental features such as landmarks), refer to (Sadalla and D. R. Montello, 1989) or (Klatzky, R. 1998). The importance of the two coordinate systems varies with the task at hand. For scene recognition, the egocentric system is the most important, whilst for reorienting the allocentric system is dominant (Klatzky, R. 1998). The spatial tasks that are intensely studied in this context are: recognising scenes, reorienting and updating (Meilinger and Vosgerau, 2010). Burgess (2006) developed a two system model of parallel egocentric and allocentric representations of object location memory. It is argued that navigation could be a translation between both systems. Wang and Spelke (2000) argue that the representation of targets is relative to the navigator self and is updated as the navigator moves through a novel environment. In the process, a cognitive map is achieved which accounts for the locomotion along the path.

Allocentric representations are usually discussed in association with the visual sense, but not in connection to the haptic sense. In the absence of visual and aural clues human navigators have to rely on what is called path integration (Mittelstaedt and Glasauer, 1991) or dead reckoning (Kalia et al., 2013). The robotics counterpart of which is usually called odometry. Path integration uses the available vestibular, kinesthetic and motor command information in order to maintain self-orientation and position during locomotion in the temporary absence of vision (Amorim et al., 1997; Etienne and Jeffery, 2004).

Experimental investigations of path integration usually comprise a learning phase, where the subjects view the scene; and a test phase, where the subjects are asked to walk blindfolded to a target point. Amorim et al., note that when subjects have to circumvent several obstacles in order to reach a previously target, their accuracy is actually better than when they walk directly to it (Amorim et al., 1997) More general, providing subjects with landmarks during the test phase of path integration improves their performance (Kalia et al., 2013).

Amorim et al. (1997) investigated non-visual (blindfolded) navigation to a previously viewed object from two perspectives. They separately investigated whether subjects would be able correctly indicate the location as well as the orientation of the previously seen object after the walk without vision. Amorim et al (1997) recall the 'rectilinear normalization' effect observed in several studies, whereby navigation and orientation judgements tend to be carried out in (and distorted toward) a normalised right-angle grid. Sadalla and Montello (1989) found that angles that are close to 0^0, 90^0 or 180^0 are the most accurately remembered. They also found that turns between 0^0 and 90^0 were all over estimated, while turns between 90^0 and 180^0 were all underestimated.

5.2 Tool Use

The lower limbs of a human being play the key role in locomotion, while the upper limbs have been made available for other tasks, for instance to use tools. Important is that tool use affects the way in which the tool-users interact with the surrounding environment (Baccarini and Maravita 2013). We can modify our relationship with external space in terms of body/space representation by using a tool; tool use induces a spatial remapping and suggests a direct expansion of the so-called peripersonal space [roughly what we above called the haptic space] to the whole space reachable by the tool (Baccarini and Maravita 2013).

The tool we are aiming for is a mobile robot with a haptic user interface. However not every object can function as an effective tool. An important requirement for an effective tool is that the tool is or becomes transparent while it is used.

A transparent tool, or more generally '*transparent technology* is a technology that is so well fitted to, and integrated with, our own lives, biological capacities, and projects as to become almost invisible in use'. In contrast, an '*opaque technology*' is 'one that keeps tripping the user up and thus remains the focus of attention even during routine problem-solving activity' (Clark, A. 2003). As Clark (2011) argues, the user does not 'feel' the equipment in his or her hands: 'Instead, the user "sees through" the equipment to the task in hand. The classic illustration of 'transparent technology' in this sense, and of particular relevance to our own study, is the use of a cane by a blind person (or 'cane traveler') for navigational purposes (Clark, A. 2003) as described by Bateson (1973: 434).

6 Interface

Following Robles-De-La-Torre (2006), active or haptic touch comprises active exploration involving in particular cutaneous and kinaesthetic capabilities. We therefore have a bias towards an interface solution that utilises these senses 'implicitly' and presents information in a non-symbolic or non-performative form; the paradigm is the handle of a guide dog discussed above. Explicit or symbolic signals would for example be that one tug on the interface means right, while two tugs mean left. We believe, though we have not tested it, that implicit feedback induces a lower cognitive load for the handler. Implicit feedback certainly aids the aim of developing a transparent tool.

Initially our project looked at three distinct interfaces: a wirelessly connecting device, for instance a Nintendo Wii, a short rope/rein or lead and a stiff handle. A major problem for any wireless device lies in how to indicate the position of the robot with respect to the follower. A rope does indicate the direction of the robot but only when there is no slack. Young et al. (2011) use a spring-loaded retractable lead design (popular with dogs), which keeps the lead taut; the retracting mechanism however obscures the length of the lead and thus the distance between the robot and the handler is not known. Our final choice has been for a stiff handle with which the distance to the robot is fixed by the length of the handle while the handle always points directly to the robot.

6.1 Interacting with a Stiff Handle:

Our first design of the handle consisted of a stick held in one hand. To investigate its exploration potential it was mounted on a disc with unpowered omni-directional wheels (shown in Figure 3). The disc would be set into motion by the person holding the stick; the omni-directional wheels made the disc easy manoeuvrable in any direction on the floor; comparable to a white cane on wheels. However, in a pilot trial, several (blindfolded) subjects immediately put their second hand on the stick (Figure 3 right), apparently trying to improve transparency. We concluded a lack of accuracy of a one handed hold, and switched to a crutch-like design (Ghosh et al., 2014a) in which the stick is fixed to the lower arm of the handler, refer to Figure 4. The angle between the part fixed to the forearm and the lower part of the handle is adjustable for the comfort of the handler. However, the angle has to be fixed; leaving it flexible obscures the distance to the robot.

Figure 3, Single hand held stick; left: full view, right: subject using two hands.

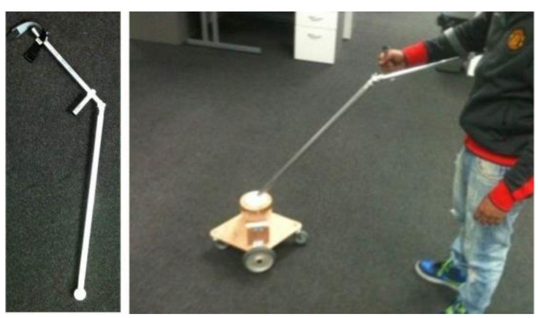

Figure 4, left: a crutch like stick design; right fixed to a subject's arm.

Our observation of a lack of accuracy of a single hand hold is in line with experiences in using a white cane. Visually impaired people using a white cane do hold the cane in one hand but they also keep the elbow touching the body. The robotic shopping trolley developed by Gharpure and Kulyukin

(2008) guides blind shoppers, holding the trolley handle, along the aisles in the shop. As the trolley handle is held with two hands we guess that accurate directional sensing is implicitly secured.

The handle depicted in Figure 4 is to be connected to the robot. As Figure 4 shows there is quite a distance between the robot and the handler (around 1 meter). Using a rigid connection, a turning movement of the robot is magnified at the end of the handle, delivering an abrupt tug to the handler, even at subtle turns of the robot. An alternative consisted of using a ball-free mechanism at the base (as presented in Figure 5, left). Pilot trials revealed that the handler lost track of the orientation (heading) of the robot, though its position (distance and direction) remained clear (Ghosh et al., 2014a). The latest design applied a mechanical spring system at the base (shown in Figure 5, right), which allows rotation of the handle on the horizontal plane. When rotating the handle, the spring system builds tension on the handle, the tension increases with the rotation angle; thus as the tension builds up the information about the turn is gradually passed on to the handler with some time delay or latency. In a certain sense the robot's behaviour becomes slightly better predictable.

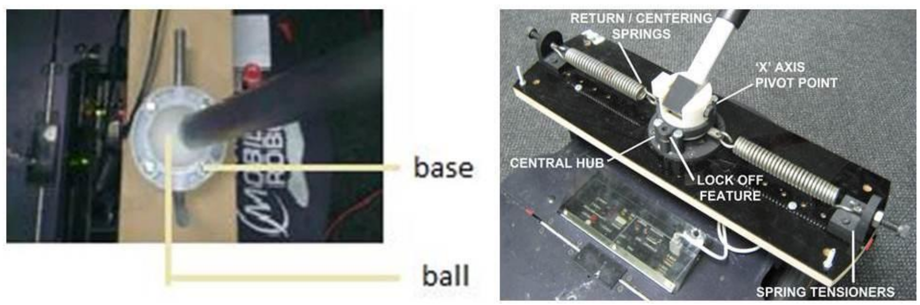

Figure 5, left: ball-free mechanism at the base; right: sprung mechanism.

7 Testing

The ultimate aim is to design and build a robot and interface that enhance confidence of the handler. Moreover, ultimately the tests should validate whether our system indeed enhances confidence. We are not yet at a stage that we can test and evaluate a full system. Below we briefly discuss the first test we have performed so far; we have separated experiments concerning locomotion guidance from some very preliminary experiment concerning exploration.

7.1 Testing Locomotion Guidance

The handle discussed above has been connected to a robot in two ways: using the spring loaded connection as well as a rigid connection. The spring connection gradually forces the handler to turn, while the rigid connection causes a tug to the handler. Below we briefly discuss the results as the full experiments have been reported in (Ghosh et al., 2014b). In these experiments the robot was programmed to navigate fixed trajectories. The operator would start and if necessary stop the robot remotely. One could say that the robot emulated an autonomous robot as it was operated independent of the handler. The robot's behaviour was restricted to pre-programmed repeatable behaviours, in order to be able to compare results. The pre-programmed trajectories consisted of a straight line (5m), a left or right turn (1-1.5m) and another straight line (3m). The turns varied, short turns were about 45 degrees while the longer ones were close to 70 degrees. The robot operated with a linear speed of 0.6m/s, while for the turns the angular speed was increased to 0.5 rad/s; turns resulted into a circle arch with a radius of about 1 to 1.5 m.

If the robot would be applied in search and rescue situations one would be looking for the safest path. The safest path for the handler is obviously the path that the robot already has traversed. From this we defined (Ghosh et al., 2014b) an evaluation metric in terms of how closely the path of the handler matched the live path of the robot. In an attempt to also quantify the experiences of the subjects with respect to confidence, calmness and comfort we used a five-point SAM scale (Ghosh et al., 2014b).

Remarkable was that the subject who scored lowest on the SAM scale on average followed the path as good as the others. However, in the test with the rigid connection - where the robot gives a tug - this subject scored slightly better in following the robot's path, while with the spring load connecting this subject scored below all others.

7.2 Testing Exploration

Exploration in the context of search and rescue entails not only finding out what there is out there; it is of life importance for firefighters to be able find the way out. Above we have briefly discusses spatial representations and path integration. We would hope that our robot and interface designs contribute positively to the spatial representation which the handler is building.

In the locomotion guidance experiments we also assessed the subject's experience of the spatial movements. To avoid that subjects had to verbalise their experience, we used drawn pictures of different trajectories and asked subjects to point to the trajectory which they believed to have followed (Ghosh et al., 2014b). There were no real mistakes between left and right turns; there were a few over estimates of the angles but no underestimates, consistent with the findings of Sadalla and Montello (1989) discussed above.

Figure 6, bumper and handle mounted on the robot.

The robot is intended as an exploration tool, for this purpose we will mount a bumper on the robot, refer to Figure 6. Haber et al. (1993) found that pointing methods using body parts or extensions of body parts (cane, stick) lead to more accurate responses. This would suggest that a handle is promising for this purpose. However, the robot is a powered device; the handler may feel that the robot slows down but no feedback as to where (front, side) the bumper hit the obstacle will be provided. A design issue is what information concerning the displacement of the bumper should be presented to the handler and how to present this.

The robot and handler will usually move into the forward direction and accidentally bump into an obstacle. This means that the front half of the bumper is the most useful part for exploration.

Suppose the robot (and bumper) have avoided the obstacle; the handler is slightly behind and should be able to remember where the obstacle was encountered. As discussed above, fire fighters advised to limit directions to the basic angles 0^0, 45^0 and 90^0. Consistent with that, Sadalla and Montello (1989) found that angles that are close to 0^0, 90^0 or 180^0 are the most accurately remembered. We are currently trying to design an experiment to test the effectiveness finer grained spatial presentations.

8 Future work

As indicated above, we are currently exploring the effectiveness finer grained spatial presentations, notwithstanding the rectilinear normalization effect discussed above. The longer term research question is to gather insight into how to guide a person using the haptic sense only, such that the person can retrace the route just followed. Should instructions be limited to 0^0 and 90^0 turns only, how does that affect spatial awareness of a longer trajectory and what role may 'haptic' landmarks play in this process.

Above, we discussed how the human handler experiences the behaviour of the robot as mediated by the interface and looked the resulting behaviour of the handler. A further direction is to let the robot learn from the behaviour of the human. A start has been made by Ranasinghe et al. (2015). They propose a mathematical model to characterise the guiding behaviour of a human guide and the reactions to that of the follower (or handler). This model could be used to adapt the behaviour of the robot and make the robot behave more 'human like'.

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