PALADYN Journal of Behavioral Robotics

VERSITA

Vision Paper · DOI: 10.2478/s13230-013-0107-7 JBR · 3(4) · 2012 · 209-217

Robot-Assisted Therapy for Autism Spectrum Disorders with (Partially) Autonomous Control: Challenges and Outlook

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Received 15-12-2012

Accepted 27-03-2013

Abstract

Robot-assisted therapy (RAT) is an emerging field that has already seen some success and is likely to develop in the future. One particular application area is within therapies for autism spectrum disorders, in which the viability of the approach has been demonstrated.
The present paper is a vision paper with the aim of identifying research directions in the near future of RAT. Specifically, we argue that the next step in such therapeutic scenarios is the development of more substantial levels of autonomy which would allow the robot to adapt to the individual needs of children over longer periods of time (while remaining under the ultimate supervision of a therapist). We argue that this requires new advances on the level of robot controllers as well as the ability to infer and classify intentions, goals and emotional states of the robot's interactants. We show that the state of the art in a number of relevant disciplines is now at the point at which such an endeavour can be approached in earnest.

Keywords

Robot-Assisted Therapy · Shared Autonomy · Theory of Mind · Autism Spectrum Disorders

1. Therapies for autism spectrum disorders

Autism spectrum disorders (ASD) refer to a spectrum of psychological conditions characterised by widespread abnormalities in social interactions and communication, as well as severely restricted interests and highly repetitive behaviour [1]. Individuals with ASD have diverse and multifaceted needs and a wide range of skills and abilities [2]. Their major impairments are social communication deficits: these affect initiating and maintaining a social conversation, understanding body language, making eye contact, and understanding other people's emotions [1]. Due to the complexity of our daily social situations and the lack of predictability from our social interactions, children with ASD demand individualized and efficacious intervention strategies [3–5].

There are a number of theories as to the underlying causes for ASD but it is beyond the scope of the present paper to discuss these in detail. However, given our later use of Theory of Mind (ToM) in the present paper, it is worth pointing out that one particular theory holds that persons with ASD may have an impaired or non-functional ToM [6][1].

One of the most efficient ways of reducing the symptoms of children with ASD is through early (cognitive-)behavioural intervention programs [7, 8], with therapies ideally starting already at the preschool age [9]. Studies investigating the effectiveness of such early therapies reported a notable acceleration of developmental rates resulting in significant IQ and language gains, improved social and decreased stereotypical behaviours [10]. Moreover, children that benefit from early intensive behavioural interventions maintained their gains beyond the end of the intervention program [11].

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[1] Theory of Mind (ToM) refers to the human ability to create an image of an agent's mental states (include one's own). The topic is richly studied in psychology, with different theories as to what exactly the mechanisms of a ToM are (the most prominent of which are theory theory and simulation theory, of which many flavours exist).

Early intensive behavioural interventions are based on principles of operant learning and focus on re-mediation of deficient language, imitation, pre-academics, self-help and social interaction skills [12], which are taught on a one-to-one basis in school and/or at home [13]. Parental participation is also considered essential to achieve generalisation and maintenance. This type of intervention is effective only when it is both intensive (i.e. approximately 40 h per week) and extensive – lasting at least 2 years [8, 14, 15]. Although intensive (cognitive-) behavioural interventions generally have meaningful benefits for young children with ASD, there are large individual differences in treatment response and most children continue to require specialised services [15–18]. More efficient early behaviour interventions focussing on children are needed to facilitate progress at a later stage, ultimately allowing adults to lead almost or entirely autonomous lives.

One of the most time intensive processes in such behavioural interventions is data collection. Data regarding the performance of the child is collected manually during each teaching session. It is then charted and typically graphed over a certain period of time. This helps parents, therapists and teachers understand what areas of learning progress most and which still need the most work. This is a significant aid in designing an effective intervention and can be the key to ensuring that the child develops all required abilities. From the practitioners' point of view, keeping appropriate data on a particular skill can be overwhelming and can interfere with the teaching process. On the other hand, researchers have similar ways of collecting data for interventional studies; different behavioural criteria are analysed manually based on the video data gained during the intervention session.

There is therefore a critical need for tools capable of increasing the effectiveness of standard (cognitive-)behavioural therapies (as well as reducing their cost) by addressing both the need for more efficient interventions and issues in data collection. Since the most important deficit of children with ASD is considered to be their social impairment [19, 20] (which is simultaneously considered the most challenging area for treatment [21]), a number of different therapeutic tools are currently investigated for their potential to improve the capacity of ASD children for social interaction and communication.

Social behavior deficits, such as a lack of an awareness of others, a lack of empathy or poor eye contact may hinder children diagnosed with ASD from actively participating in simple social play or games [1]. The Weak Central Coherence theory links together social deficits of ASD individuals, the impaired ability to derive generalised meaning from the context and the preference for detail-focused processing [22]. The theory argues that human behaviour is complex and subtle, thus almost impossible for ASD children to imitate (even though the same behaviour does provide obvious role models for imitation and social skills development). Social situations in particular contain an incredible amount of information, overwhelming ASD children, who cannot decide which pieces of information are relevant. For instance, it has been suggested that the perception of biological movement is impaired in children with autism from a very early age, generating a cascade of consequences for social development [23]. The same researchers also found that children with autism were sensitive to non-social contingencies normally disregarded by typically developing children. Similarly, it has been found that children with autism treat human faces as physical contingencies rather than social objects, thus for instance fixating on mouths because of the physical contingency between sounds and lip movements [24].

With this in mind, recent data – framed in the context of earlier studies that view animals as "actional agents" while humans are "attitudinal agents" [25] – indicate that children with ASD can understand animal communication better than human communication [26]. Dogs for instance appear to communicate their intentions on a level that children with ASD find easy to understand. Moreover, the authors conclude that using other agents during therapy can increase the motivation of the child in social situations. Studies also show that there is a significant improvement of language and positive social behavior during therapy sessions in which an animal is introduced (compared to using only standard therapy) [27]. One particular study [28] evaluated the increased frequency of social initiation by children with ASD from repeated interactions with a dog. This should be taken into account when planning therapeutic interventions whose aim it is to increase the social skills of children with ASD in general, and empathy and theory of mind in particular [26, 29]. Overall, the literature supports the positive effects of introducing therapeutic animals in the intervention plan for children with ASD for improving social skills [29].

2. The case for therapeutic robots

However, animal assisted therapy also has some significant limitations that need to be taken into account. For instance, animals are difficult to control, retain a certain unpredictability even if well-trained and may carry diseases or trigger allergies. For that reason, the use of robots rather than animals is attractive since they retain the communicational simplicity of animals but overcome some of their disadvantages. An emerging field in this context is therefore Robot Assisted Therapy (RAT), which is increasingly used to improve social skills in children with ASD [30–32]. RAT can be used as a complementary therapy for ASD children, has the potential to reduce the workload of the therapist (and hence the cost of the therapy) and to improve the social skills of these children, thus giving them the opportunity to function in society. Given the current rapid progress in technology, a large potential for innovation in treatment procedures for children with ASD exists.

Several studies (as also discussed in the previous section) hypothesise that ASD individuals engage more successfully in social interactions if social information is presented in an "attractive" manner (i.e. that is easily understood and clearly identifies the expected behaviours) [33]. Together with the previously discussed preference of ASD children for interacting with "actional agents" as well as their need for predictability and simplified social situations, the advantages of robots in therapeutic scenarios become readily apparent. First and foremost, a (possibly humanoid) robot can simultaneously offer both human-like social cues and object-like simplicity. The use of robots in therapeutic sessions for children with ASD is therefore a promising development [31] since it directly plays to the fact that children with ASD exhibit strengths in understanding the physical (object-related) world whilst having a relative weakness in understanding the social world [23].

Robots can also be constrained in a controlled manner to communicate only relevant information to avoid overly complex situations that may distress the child. They can further be used to repeat the same information or scenario repeatedly whilst avoiding trainer fatigue. Finally, robots are predictable and therefore controllable. Errors can be made safely; the therapies can be used to train a wide range of social and communication behaviours while simultaneously allowing individuals to work according to their own abilities in preparation for exposure to such stimuli in real life.

These advantages are corroborated by several studies. Children with ASD have long been known to be more responsive to feedback, even social feedback, when it is administered via technology rather than a human [34]. A number of research groups have specifically examined the response of children with ASD to robots [30, 35–37]. It has thus for instance been shown that ASD children pro-actively approach robots [38] or that robots act as a mediator between the child and the therapist [39]. Robots are used in play therapy [40] and elicit interaction [41] as well as joint attention episodes between a child and an

adult [42]. Researchers have for instance used the “huggable” robot Probo for social story telling [43], to support children in the recognition of basic emotions [44] and to mediate social play skills of children with ASD with their sibling [45]. ASD children also showed more social engagement when interacting with a Nao robot compared to a human partner in a motor imitation task [46]. A recent review [47] presents a comprehensive overview of different robots used in different roles within ASD therapies as well as the different approaches that exist.
In the context of current therapeutic approaches that are used for ASD children, there are several attempts at categorising the applications for social robots. For example, Diehl [31] categorises clinical applications of robots into four classes, namely:

1. Responses to robots or robot-like characteristics [48–54]
2. Eliciting behaviors [36, 40, 55–62]
3. Modeling, teaching or practicing skills [63]
4. Providing feedback or encouragement [63, 64]

All of the above demonstrate that robots generate a high degree of motivation and engagement in children, including in particular those who were unlikely or unwilling to interact socially with human therapists. Overall, this underlines the potential of using a robot as a “social crutch” [41] to engage children, teach them social skills, and assist in the transfer of this knowledge to interactions with humans. It is however equally important to note that not all participants improved their performance after robot/child interaction sessions.

3. The need for a developmental, adaptive approach

While the benefits of the presence of a robot in a therapeutic intervention are undisputed, current approaches typically restrict themselves to a Wizard of Oz (WOZ) setup [65, 66] in which the robot is usually remotely controlled by a human operator unbeknownst to the child (while it can occasionally be operated by the therapist himself). The immediate benefit is that this allows a focus on (social) interaction without the actual need to implement sophisticated behaviours in the robot.
In the long-term, however, there is a need for therapeutic robots to increase their autonomy, both to lighten the burden on human therapists and to provide a consistent therapeutic experience. Further, only acting on the directly observable movements of the children is not sufficient since the psychological disposition (reflected by emotions, intentions, and goals), together with the past history of the patient, play a crucial role in improving the quality of the social response of the robot. Since these children are all very different, personalised behaviours are required for truly child-specific interactions and therapies.
Few of the existing approaches in RAT involve autonomously interactive robots or use data from the interaction between child and robot to make, fine tune or quantify diagnoses. They also do not attempt to construct predictive models of ASD children’s behaviour, which could then be used to guide the interaction over a longer time period (as opposed to interactions constrained to a single therapeutic session) and to adapt the interaction to the individual needs of the child (although some work in that direction exists [64, 67]), which is very important given that autism disorders manifest in a spectrum rather than well-defined ways. Rather, most of today’s therapeutic robots (for ASD) are in essence remote controlled devices; they typically have no or little autonomy[2] and are thus not yet reducing the workload of the therapist. Often, they even require extra personnel to manage the technical aspects of the robotic software and hardware, in addition to the wizard operating the robot. Significant work therefore remains to be done [47].

The main purpose of the present paper is to consider the state of the art in robotics and related research with the specific purpose of considering the feasibility of moving towards more autonomous robots in the sense just discussed. We argue that this is indeed possible and that any such approach will necessarily benefit from a developmental perspective since hard-coded behaviour is neither fruitful nor desirable in this context (autism disorders manifest on a spectrum, which implies a need for individualised robot behaviour).

The next two sections focus on the potential to infer ASD children’s internal states and desires from observation alone, which we argue is a necessary prerequisite for a robot to be able to interact with the children with some degree of autonomy. The following section then briefly considers approaches to control for therapeutic robots (and, generally, social robots). In particular, it is argued that such control should be independent of a specific platform to facilitate broad adaptation. We conclude by considering once again the developmental angle and how it benefits the aspects discussed in the previous sections. Overall, we suggest that researchers interested in developmental robotics would find the specific case of therapeutic robots an application area with a lot of potential.

4. Assessing child behaviour

A crucial next step within the field of RAT is to move beyond the reliance on WOZ control of robots in therapeutic settings [47]. Although full autonomy (in the sense that the robot can adapt to any event during the therapeutic sessions) is currently unrealistic, it is feasible to aim at a “shared autonomy”, where the robot user (the therapist, psychologist or teacher) gives the robot particular goals and the robot autonomously works towards achieving these goals. This does not remove the caregiver: the robot would merely have an episodic degree of autonomy while the overall therapeutic session would remain under the control of a professional therapist[3]. However, even autonomous behaviour as constrained by the above requires some ability by the robot to infer the intentions of the child it is interacting with. This in turn implies at least some access to the child’s mental states (intentions, motivation and so on). Here, we therefore focus on research indicating that such an endeavour is indeed feasible (although by no means trivial).

ToM, introduced earlier, is a relevant concept here, since the creation of computational (predictive) models able to predict the behaviour of human mental states (which presupposes the ability to estimate such states) can be seen as a machine implementation of some aspects of this human ability[4]. Although, it can clearly not be claimed that endowing a machine with a fully-fledged ToM in the human sense of the term is possible, steps in this direction would serve the dual purpose

[2] especially in the sense that they do not typically autonomously adapt to the behaviour of the child (but see for instance the aforementioned [64]); other types of autonomous behaviour exist; for instance the ability to play games autonomously [62].
[3] Which is also important given ethical considerations raised in this respect [68]. Reviewing those in detail would however go beyond the scope of the present paper.
[4] The present section is thus not concerned with ToM as related to putative causes of ASD but ToM as an inspiration for robot controllers.

of facilitating the choice of most appropriate robot behaviour and facilitating record keeping on the children's progress over long periods of therapy. More specifically, endowing robots with a rudimentary ToM could allow them to act based on the children's internal states of goal, desire, and intent rather than on explicit actions. Furthermore, a robot that can recognise the goals and desires of others will allow for systems that can (1) react more accurately to the emotional, attentional, and cognitive states of the interaction partner, (2) learn to anticipate the reactions of the interaction partner and (3) modify its own behaviour accordingly (in addition to the ability to better predict the outcome of their own actions).

In general terms, the creation of a ToM for a robot is of course a hard problem since it requires capturing the richness of the human mind without being realistically able to assume the existence of a teaching signal in all cases. In the specific case of RAT, however, the interactions between the children and the robot are constrained to therapy settings. In addition, human experts (the therapists) are available to provide training data for any computational model implementing a ToM. Implementing ToM-like mechanisms in robots aimed at ASD therapy therefore fulfils the dual purpose of improving RAT and furthering research into how such ToM mechanisms can be constructed in the first place.

It should be noted in this context that the technology for developing basic prerequisites of a ToM does exist, even if robots capable of representing epistemic mental states of other agents remain to date a desideratum. An early proof of concept dates back to 2002 and had two abilities [69]: distinguishing between animate and inanimate motion as well as identifying gaze direction. By building artificial systems that possess these two characteristics, simple autonomous social interactions, beneficial for teaching basic social skills to children with autism, can take place. Another step towards "understanding" robots for use in future ASD intervention was taken in the development of a physiology-based affect-inference mechanism for robot-assisted intervention, allowing the robot to detect the affective states of a child as discerned by a therapist and adapt its behaviours accordingly [64].

Computational models of ToM-like aspects also exist. A computational model replicating some behavioural deficits observed in ADHD children has for instance been presented [70]. Markov Random Fields have been suggested as a modelling approach suitable to a ToM and have been shown to replicate a number of experimental findings, including, in particular, aspects of joint attention (gaze following) [71].

In the following, we discuss research and insights relevant for the creating of a robotic ToM, focussing in particular on relevant data that can be obtained from observation alone. Although there are a number of on-body sensors that could provide interesting data in this respect [72–76], their use is often not preferred in RAT since ASD children for instance can be hypersensitive, resulting in the perception of touch as excruciating. The fear of being touched can also cause a panic attack [77].

5. Inferring internal states from observation

Relevant robot work so far tends to focus more on communication (verbal or not), including for instance the development of language [78] or the grounding of language [79, 80]. Within human-robot interaction in general, "internal" states of a human are typically considered insofar as they refer to the goals of actions, which has led to some of the robotic work to be inspired by neurophysiological research into mirror neurons. It has for instance been shown that mirror neurons are organised into pools encoding specific components of an action as well as the (object-oriented) goal of the overall action containing this component [81]. This insight has led to computational models for "chaining" motor primitives into complete actions, including the ability to infer the goal of the action [82–84]. As such, this type of research provides insights into important internal states (goals) but is in itself not sufficient to cover all aspects needed for a robotic ToM.

Gestures are of interest in this context since they are also a means of communication and may indicate, for instance, joint attention or even emotional states. Specifically, gestures are meaningful body motions involving head, face, hands and fingers, arms, shoulders or body for the purpose of interacting with the environment or displaying a message [85]. In the present context, the main gestures of interest are likely to be those involving the arm/hand and the head (e.g. pointing with a finger, nodding with the head), which display important information during human-robot interaction. There is work that builds upon such aspects to explore distal interactions between humans and robots; exploring for example attentional behaviours as nonverbal communicative signals in virtual environments [86], or simply a range of gestures in an embodied robot [87]. Some gestures indicate how an interaction is proceeding and how engaged the participants are, while others play specific roles. Nodding, for instance, is grounded in previous communications [88] and looking conveys either attention for what is coming, directs attention to environmental affordances/objects, or indicates a lack of interest in the interaction.

Also relevant is the fact that gestures and whole body motion (including facial expressions) are critical components with respect to observing the states of mind (including emotions) and intentions of people. Some studies suggest that we are able to identify the intentions of others based on motion information [89–91]. This ability of humans, and other animals, to reliably detect and recognise the intention governed actions of conspecifics has been studied within the area of biological motion perception, with some findings from these studies [92, 93] indicating for instance that human vision is highly sensitive to the movement of other individuals (natural human actions can be generally recognised within around 300 milliseconds [94]).

The ability to visually perceive intention governed actions allows us to successfully interact with people around us. It has been shown that human observers consistently segment simple hand and arm actions on the basis of movement kinematics [95, 96]. More specifically, there is a significant relationship between segmentation behaviour and velocity or acceleration and change of direction for the hand and arm actions. The general research findings in this area indicate that our ability to understand the actions of others relies importantly on perceiving the moving parts of the human body.

A further aspect of interpersonal interaction concerns the perception of emotions. Basic emotions (e.g., anger, disgust, fear, happiness and sadness) also appear to be conveyed in human movement presented in point-light displays [97]. Simple movements such as knocking and drinking [98] can also reliably convey emotion. The upshot of these studies is that the kinematic information in human movement also appears to be effective at conveying more high-level information about the intentions and emotional states that occur in interpersonal interaction.

Given that autism disorders manifest on a spectrum, with large inter-individual differences, one has to consider what one would need to infer specifically. There are however a number of behaviours that are relevant across the spectrum, even if their exact interpretation may differ between individuals. This can include, for instance, the level of verbal instruction that the child understands (including the complexity of the word since some children may only understand a couple of simple words), the personal space that some children need (maintaining an appropriate distance is in some cases very important), information about their level of interaction and signs of frustration (indicated by behaviours such as fast blinking, hand flapping, covering ears with hands). Some children may also have different reactions regarding the feedback that they can receive from the robot; for some children multiple sounds are required in a high volume and for others only a single sound in a low volume is enough. It is possible to observe which type of feedback they respond better to and then repeat that sound in the session. Finally, it is also important to detect repetitive behaviours, although it has to be kept in mind that these can indicate both frustration and enthusiasm.

6. Adaptive, platform-independent control beyond WOZ

There is a need for progress in the understanding and implementation of control architectures for social robots with specific applications in RAT. This has at least two reasons. The first is that such a controller needs to operate with some degree of autonomy, as previously discussed. The second is that RAT is ultimately an applied field and may, in the future, see a number of therapists working independently within this framework. It is therefore not reasonable (or indeed desirable) to focus one's efforts on merely one specific robot. Rather, the controller implementing the higher level ("cognitive") functions of the robot should be as platform-independent as possible. This section considers such control given these constraints (focussing on the second issue since the first has been previously discussed).

Most control architectures for autonomous social robotics rely on behaviour-based architectures [99]. The advantages of using a behaviour-based solution is that the system is reactive and responds timely to (social) cues. It is also excellent at blending different behaviours and responding to external sensory input using an adaptive mix of inhibitory and excitatory activations. However, behaviour-based approaches tend to only operate in the here and now and are not capable of anticipating upcoming interactions by ASD children nor are they particularly suited for longer-term planning and social modalities that require a different temporal perspective, such as linguistic interaction. Francois et al. [100] demonstrated that adaptive robot behaviour is more efficient than a reactive controller for a touch play game using an Aibo ERS-7. Through including the child behaviour assessment previously discussed, the robot can autonomously adapt its behaviour in a learning task to the engagement and performance level of the child.

As there are only a few control architectures tailored to social robotics, there are almost none specific to social robotics for therapeutic purposes. Previous work includes the use of an affect space coupled to facial expressions (cf. [101]) to animate an expressive head [102]. In [103], a bioinspired action selection mechanism (HAMMER) is used to infer the user's intention and select the next action for a simple interaction task on a humanoid robots. B^3IA is a control architecture for autonomous robot-assisted behaviour intervention for children with ASD [57]. The architecture is behaviour-based and has been specifically designed to allow non-experts to combine small behaviours that are then executed on the robot. While this approach certainly has its merits, there is a need to go further by having the architecture (a) support non-reactive behaviours, which is needed for example for natural language interaction and (b) be sensitive to the behaviour model that the robot has of the young user.

A cognitive controller outputs the social actions of the robot, including non-verbal (facial and body) and verbal expressions. Most of the generic robotics software platforms are intended for industrial robots (manipulating robot arms), mobile robot platforms (navigation) and, more recently, service robotics. Typical cognitive controllers are thus specific to the particular robot design they have been developed for. There has been a large push in developing common robot operating systems, such as ROS of Willow Garage [104], OROCOS [105], URBI [106] or Robotics Studio of Microsoft [107]. These robot operating systems provide common descriptions and interfaces to sensors and manipulators on mobile platforms. However, there has been no or little development towards a common "social operating system" for robotics. There is a large variety of social robots, with NAO [108], Kaspar [62], Probo [109] and Keepon [110] being examples with completely different morphologies and social capabilities, and just as a common robot operating system makes sense for mobile robots, so does a social robotics operating system for social robotics. Such a cognitive controller needs to be independent of the robotic platform, as such generic methods are required to control the robot's expressions, gestures and mobility. In the following section, we briefly sketch some of the required functionalities for this kind of controller.

7. Necessary functionalities of social cognitive controllers

In behavioural psychology and AI, it is has been beneficial to see behaviour (or, more generally, cognition and information processing) as being organised in three levels [111, 112]: the reactive layer, the deliberative level and the reflective level (or meta-level). Here, we consider how these levels would map onto a social cognitive controller.

The reactive subsystem is constituted of the lowest-level processes. In natural systems, these processes are genetically determined and not typically sensitive to learning. State information, coming from the sensory inputs, is immediately acted upon with appropriate motor outputs. The reactive subsystem, while absent in many robot systems, is essential in social robots. It creates the illusion of the robot being alive, and acts as a catalyst for acceptance and bonding between the young user and the robot [113].

The deliberative subsystem needs to select behaviours based on the direct processed sensory input (as well as on the child behaviour analysis to address the anticipatory aspects of social interaction) from available integrated robot behaviours. Given algorithms for behaviour analysis, the robot needs to be able to detect when the child gets disengaged or bored and to autonomously adapt its behaviour to this. It further needs to be able to adapt the complexity of the task according to the needs and performance level of the child. Overall, This system should be independent of the required scenario, so that for example imitation, turn-taking or joint attention interventions can be generated with the same framework.

The system should then select actions to produce the interaction appropriate for the selected therapeutic goal. Most action selection mechanisms have been designed either for robots executing tasks or to simulate biological action selection mechanisms [114]. An attention system determines the robot's focus of attention [115]. Attention emulation is introduced so partners of an interaction can orient attention to an object, event or person. This subsystem is important since, generally speaking, people with ASD avoid eye contact and have difficulties following the gaze or deictic pointing of others [116]. Expressional and actuation subsystems are responsible for generating believable human/animal-like smooth and natural motions and sounds that are platform independent. A mapping between facial and body action units and motor controllers is only made at this final step.

As argued before, to make a control method usable for all kinds of robots, it naturally has to be independent of the physical implementation of the robot, which is not typically the case in current approaches where the motors and actuators are often controlled directly. For example, facial animation implemented in Takanishi's WE-4RII robot [117] or Ishiguro's geminoids are often pre-programmed offline or are generated by human motion tracking [118] and are always heavily dependent on the morphology of the robot [119]. The Facial Action Coding System (FACS) [120] has previously been used to abstract away from the physical implementation of the robot face [121, 122]. FACS decomposes different human facial expressions in the activation of a series of Action Units (AUs), which correspond to the contraction or relaxation of one or more human muscles. For example, expressing the emotion surprise requires the activation of AUs corresponding to the raising of the inner and outer eye brow and the upper eye lid while happy requires cheek raiser and lip corner puller. The physical actuation of AUs will depend on the morphology of the robot: a mapping will be needed between AUs and physical actuators. This mapping will be specific to a robot platform and developmental approaches can be used to learn this mapping on-line.

Although the social robot will be under constant supervision of a therapist or teacher, its cognitive controller should act autonomously and therefore requires a kind of self-monitoring system which is the meta-cognition level of the robot and needs, in the simplest form, to be implemented as an alarm system [123]. It has to watch over the internal processes and interrupt the behaviour of the robot when technical limits (designers cannot anticipate all possible situations) or ethical limits (e.g. avoiding persisting on interaction when the child refuses collaboration) are reached. Therapists should also be able to interrupt the behaviour of the robot if the latter is judged to act inappropriately. An open question here is whether such an interruption should be hidden (e.g. in the form of a code word known to the robot) or explicit (such as explicitly reprimanding the robot so the child understands that the robot was acting incorrectly. This may be part of the learning process of the child and adds to the believability of the robot as a social agent).

8. Developmental robotics for therapy

Overall, what the exposition above demonstrates is that there is a large potential for the ability to identify internal states based on observable variables. Application of these insights to ASD is relatively novel, with limited explorations in using metrics such as gaze direction in an effort to highlight the viability of the approach in diagnostic applications [124]. Furthermore, a model capable of detecting (with the assistance of a therapist) affective states of ASD children exists and has the ability to remember individual preferences [64].

We argue that the successful approach to RAT for ASD will involve robots that can both differentiate between different ASD children (given that the disorder manifests in a very large spectrum, it is not reasonable to make too many prior assumptions) as well as track the development of a child longitudinally (since the therapy will presumably have a lasting effect). The robot therefore has to be able to adaptively "learn" both inter-individual differences at one time point and intra-individual differences over time. Developmental robotics possesses the tools to address such issues since there is a fundamental focus on the robot to develop its abilities rather than have them hard-coded.

The ability to perform the tasks above allows the development of novel diagnostic/reporting tools, which take advantage of the patient-robot interaction as also argued by [124, 125]. Data acquisition during therapy is vital to understand whether the therapies are working and to characterise the progress of the child. Yet, to date, the methods used to this effect are mostly restricted to observation (video-based annotation), questionnaires, and interviews. Algorithms that are able of tracking the development of a child longitudinally and differentiate it from other children (together with sensory data that would necessarily have to be recorded to achieve the control) thus have the potential to both provide quantitative data about the development process and to at least partially automate the (currently manual) analysis.

In order to successfully assess children's behaviour, the robot would likely track a number of data sources including the duration, number, type and order of identified behavioural states that the child went through in a session; including for instance events in which the child's reaction to a robot action did not match a previously accurate prediction (which may indicate a change in behaviour). Overall, all of the above can therefore contribute to diagnostic evaluations.

9. Conclusion

This paper has presented the field of RAT[5] as an applied domain in which developmental methods have a large potential to further the state of the art. In particular, we have highlighted that sufficient research exists to now attempt the creation of algorithms that can assess the behaviour of children with a view to allow some degree of autonomy in the robot's interaction with children. It has to be stressed that we mean autonomy in the sense that the robot can adapt to the changing needs of the children over time; not merely, as in most existing work, carry out certain given tasks (such as playing games) autonomously. We have also discussed requirements on the controller itself, arguing in particular for a need for platform-independence, and sketched some of the necessary requirements.

Overall, RAT is an exciting field, both for its potential to improve existing therapeutic approaches (including the therapy itself and, as discussed, the diagnosis and the long-term tracking of children' progress) and for the technical challenges it presents. At the same time, since the setting in which a robot would operate remains relatively constrained and an expert (the therapist) is always available for feedback, it is also a field in which technological progress can reasonably be achieved at a fast and productive rate.

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