The Iterative Development of the Humanoid Robot Kaspar: An Assistive Robot for Children with Autism

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Abstract. This paper gives an overview of the design and development of the humanoid robot Kaspar. Since the first Kaspar robot was developed in 2005, the robotic platform has undergone continuous development driven by the needs of users and technological advancements enabling the integration of new features. We discuss in detail the iterative development of Kaspar's design and clearly explain the rational of each development, which has been based on the user requirements as well as our years of experience in robot assisted therapy for children with autism, particularly focusing on how the developments benefit the children we work with. Further to this, we discuss the role and benefits of robotic autonomy on both children and therapist along with the progress that we have made on the Kaspar robot's autonomy towards achieving a semi-autonomous child-robot interaction in a real world setting.

Keywords: Autism therapy, Humanoid social robots, User-centered design.

1 Introduction

Investigating the potential of using robots as assistive tools for children with Autistic Spectrum Condition (ASC) emerged as an area of research during the late 1990s with K. Dautenhahn and I. Werry pioneering studies in this area [1]. Initially research in this area was conducted with mobile robots, but soon after the possibility of humanoid robots was also investigated using a small robotic doll called Robota [2]. The Robota robot had 5 Degrees of Freedom (DOF) in total and was one of the first humanoid robots used for robot assisted therapy for children with ASC. The Robota robot had the appearance of a pretty doll and could move its arms legs and head to interact with children. In 2004 Kozima et al. [3] also published work investigating how a child with ASC interacted with a humanoid robot called Infanoid that possessed 29 DOF. Unlike Robota, Infanoid did not have a human face. Robins et al. [4] investigated how the appearance of a human and a robot interacting with children with ASC can

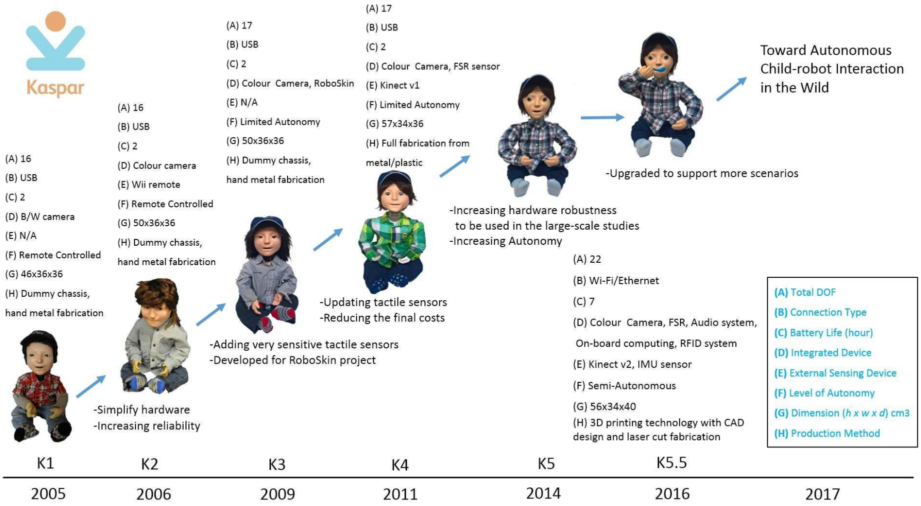

Fig. 1: The Kaspar robots generation 1 to 5.5 and the year of manufacture.

influence the interaction. Robins et al. [5] found that appearance can have a substantial impact on the children’s desire to interact with a human or a robot. The lessons learnt from these studies were carried through into the development of the humanoid robot Kaspar which is the subject of this paper. The following section gives an overview of the iterative development of Kaspar as shown in Fig. 1.

2 The Kaspar robot

Since 2005, 5 generations of the Kaspar robot have been developed (see Fig. 1) to be used as a therapeutic tool in the hands of therapists and also as a research tool enabling researchers to explore the possibilities of human social dimensions in many human-robot interaction studies. The first prototype of Kaspar (K1, 2005) was manufactured from hand fabricated metal parts, equipped with minimal sensing capability and was only capable of being controlled remotely during child-robot interaction scenarios. While the most recent generation of Kaspar (K5, 2016) has been manufactured using a 3D printing technology with CAD design and laser cut metal parts. The K5 robots are equipped with much more advanced hardware and software which enables reliable and repetitive semi-autonomous child-robot interactions. These K5 robots have been tested and used in several real-world scenarios in both special needs and mainstream schools [6]. Thanks to recent advances in sensing technology and computing techniques, the K5 robots have the ability to perceive the environment, make decisions about the observed social cues and events to interact and react to these cues through body gesture, facial expressions and vocal communication. The following sections explain the development journey of the Kaspar robot.

2.1 The first Kaspar robot (K1)

The humanoid robot Kaspar (K1) was initially developed and prototyped in 2005 by M. Blow et al. as a Human-Robot Interaction research platform [7]. The head components were originally designed by A. Appleby as his MSc Project, and construction was started by M. Blow and completed by M. Walters. Due to the humanlike appearance of the robot with realistic but simplified features, Kaspar was quickly adopted to investigate the use of robots as therapeutic devices for children with ASC [5]. The K1 robot was approximately 46cm high * 36cm wide * 36cm deep and used a 2 year old dummy body as the main chassis. A key feature of this robot was the humanoid face that could produce simple but realistic expressions. The robot had a total of 16 DOF and was powered by one 12VDC low voltage lead acid gel battery with an operation time of approximately 2 hours and a re-charge time of 4 hours. The robot used a range of relatively low cost RC servos for the arms, neck and mouth of the robot, whist micro RC servo's were used for the eyes of the robot [7]. These components at the time were chosen to strike a balance between cost and performance. One of the principles behind the Kaspar robot was to produce a robot that would cost less than 2000 euros. This robot was used for various activities and games that encourage turn taking and the exploration of facial expressions [8, 9]. The games that this robot enabled represented a huge leap compared to the Robota robot that was previously being used. The second implementation of Kaspar (K1-L) used a second original head designed by A. Appleby and arms and body designed and constructed by M. Walters in 2006. This robot was much larger than the first implementation using the body of a 6 year old child shop dummy measuring approximately 123cm high * 30cm wide * 57cm deep. The design of K1-L was largely similar to the previous version, only much bigger and mounted on a desktop PC. The robot was fitted with an extra DOF in each arm, giving it a total of 18 DOF, and additional sensors including a laser depth camera and joint feedback sensors. The primary use of this version of Kaspar was for the early software development for the iCub project and various other Cognitive and AI software development, testing and HRI studies [10]. This version of Kaspar was never intended for use with children with ASC because it would be logistically unviable to take to schools. All future versions of the Kaspar robot were designed to be used for children with ASC in schools or home and were designed to be transported in a suitcase and would have the development of their features focused on this user group.

2.2 The second Kaspar robot (K2)

The second version of the Kaspar robot (K2) was designed and created by M. Walters in 2006, and was similar in specification to the K1 robot measuring approximately 50cm high * 36cm wide * 36cm deep with the same 16 DOF, but benefited from a re-designed head to simplify the internal hardware and included colour on-board cameras as an improvement on the black and white cameras of the previous version. The construction of the K2 robot was largely driven by the need for an additional robot to conduct more research into the potential applications of the robot working with children with ASC. This robot in particular was the first robot of its kind to utilise a Nintendo wii remote to facilitate a fully autonomous collaborative game for children with ASC. Wainer et al. [11, 12] developed a system with the Kaspar robot that could utilise the wii remote to play dyadic and triadic games with children with ASC. The game was created because of the positive response of children to the K1 robot in previous studies [8] and the availability of new technology at the time [13]. The K2 robot was used along with a small monitor and wii remotes for each player, including the robot. Each player had a wii remote strapped to their arm and had to collaborate to earn the reward in the game. Two studies were performed, a dyadic study [11], comparing how children play with a human player compared to playing with Kaspar, and a triadic long-term study [12] where children played triadically with Kaspar, all players having an equal role in the game. Before and after the intervention phase, the children played dyadic games with each other. The practical lessons learnt from this study and in particular these technical developments, were that making a robot fully autonomous does limit the children that can be worked with. In previous studies children with ASC on the lower end of the spectrum worked with the robot. However in this type of fully autonomous setup, it was not possible to work with low functioning children because of the rigid and scripted nature of such games to enable an autonomous system to operate. In addition to this, having devices that need to be attached to the children themselves is not ideal because these devices can come loose, be moved and distract the children. Taking both of these lessons into consideration, the future development of the robot and activities developed for the robot would be focused on semi-automation rather than full automation because of the limiting nature of implementing such a system. In addition to this, sensors such as the wii remote that required the children to wear them were not used in future studies because of the potential technical issues and possibility for the sensor being worn to distract the child.

2.3 The third Kaspar robot (K3)

The third Kaspar robot (K3) measured approximately 50cm high * 36cm wide * 36cm deep, with 17 DOF and was developed in 2009 by M. Walters specifically for use in the European ROBOSKIN project. The project was focused around developing and testing robotic skin that could facilitate tactile interaction. The specification of K3 built on the previous versions in a number of ways according to what had been learnt from previous versions of the robot and previous studies, conducted with children. Unsurprisingly the most notable development on K3 was the implementation of tactile skin patches strategically placed on the robots feet, hands and chest to detect tactile interaction and enable the robot to assist children learn about what is and is not appropriate tactile interaction. The tactile sensors on the robot were called ROBOSKIN and used distributed pressure sensors based on capacitive technology. The transducer consists of a soft dielectric sandwiched by electrodes. When force is applied to the sensor patch the distance between the electrodes change, causing the capacitance to change accordingly. The ROBOSKIN system in particular was constructed with a number of tactile elements (taxels) geometrically organised in interconnected modules of triangular shape. The flexible PCB was covered by a layer of silicone foam and acted as a deformable dielectric. Further to the tactile sensors, an additional degree of freedom in the torso was added, enabling the robot to turn and perform more complex gestures. This additional DOF was particularly useful for enabling the robot to turn away from the child when the child had hit the robot, which could now be detected via the tactile sensors on the robot. Further to this a speaker was also integrated into the robot which helped in giving the effect that the robot was speaking, rather than using the speaker from a laptop or additional source. The robotic skin on Kaspar was successfully used to facilitate robot assisted play with children and demonstrated how tactile interaction could open up a new rang of activities to assist with the development of children with ASC [14, 15]. As a result all future iterations of Kaspar would include tactile sensors on the robot and would also include an on-board speaker as well as the additional degree of freedom that enabled movement of the torso.

2.4 The fourth Kaspar robot (K4)

The fourth incarnation of the Kaspar robot (K4) was developed outside of the University by Merlin Systems Corporation Limited in 2011, with a production run of 7 robots being produced to enable teachers to use the robots with children. This version of the robot measured approximately 57cm high * 34cm wide * 36cm deep, had 17 DOF and included a totally new body design that was fabricated from scratch using metal and plastic parts rather than being based on a 2 year old dummy as a chassis like previous versions of the robot. This was the first version of Kaspar that was used by teachers in schools. The design of the robot was inspired by the K2 and K3 robots, but was crafted using a metal chassis and plastic components. The specification for the design was largely derived from the specification of the K3 robot, in terms of the number of degrees of freedom, incorporating 10 tactile sensors and integrating a speaker into the body of the robot. However, the tactile sensors used in this robot were Force Sensing Resistor sensors (FSR), and were much cheaper and simpler than the robotic skin that was used on K3, but still provided the functionality required for the interactions with children. Using these sensors effectively allowed the robot to stick to its original design principles outlined in 2005 that the robot should cost no more than 2000 euros in components. To utilise these sensors effectively the software for the robot required extensive development. Initially G. Barbadillo integrated the FSR sensors into the Kaspar software [16], this was later refined by O. Novanda to eliminate the electrical noise from the sensors. The K4 robot was the first robot to use the Dynamixel AX-12 servos as standard. These servos were installed on the K1, K2 and K3 robots as upgrades to increase the robustness and accuracy of the robots joints. The K4 robot was also initially equipped with an on-board PC complete with Ethernet and Wi-Fi connectivity. However, the software that had been developed for this PC was not sufficiently user friendly or reliable to be used and was later replaced with a serial connecting via a USB cable similar to previous versions. These robots were used in a number of studies and allowed the robots to be used outside of the immediate research team in the university [17].

2.5 The fifth version of Kaspar (K5, K5.5)

The fifth version of Kaspar (K5) was developed by M. Walters and L. J. Wood in 2014, with a production run of 20 robots being produced. This version of Kaspar was radically re-designed to utilise modern design and manufacturing methods such as CAD design and 3D printing for ease of volume production. The main purpose of this robot was to enable larger scale studies to be conducted and for the first time to allow both parents and teachers to use the robot with children without a researcher present. The K5 robot measures approximately 56cm high * 34cm wide * 40cm deep, maintains the features of the previous versions and also includes a number of new features[1].

– Servos - The K5 robot has 22 DOF with 3 DOF in each eye/eyelid, 2 DOF in the mouth, 3 DOF in the neck, 5 DOF in each arm and 1 DOF in the torso. Two different types of servo were used, the servos for the eyes were Hitec HS-82MG servos whilst the rest of the joints used the Dongbu Robot Herkulex drs-0101 and drs-0201 servos. The Herkulex drs servos have a built in function capable of providing a flexible and elastic response to external force. This feature enabled the children to move the joints of the robot, made the robot much less prone to

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[1] https://youtu.be/Q6lRefbmDGo

breakage, more reliable and also enabled more tactile games to be developed for the robot without fear of the children breaking the robot.

- Sensors - The robot has 15 FSR sensors for tactile interaction which are distributed as follows: 2 in each hand (on the palm and back of the hand), 1 on each arm, 1 on each leg, 1 on each foot, 1 on the chest of the robot and 4 in the face of the robot.
- Connectivity - The K5 robot utilises a Wi-Fi connection so the robot can be operated wirelessly, a feature which was not available in previous versions of the robot.
- Batteries - The robot uses two 12v 7Ah Lithium Iron Phosphate batteries which can power the robot for up to 7 hours. The recharge time of these batteries is 6 hours, but is capable of a much faster recharge time with a 7amp charger.
- Speaker - This version of the robot was the first to have a head mounted speaker to help with the illusion of the sound coming from Kaspar’s mouth.
- Concealments - Previous versions of the Kaspar robot had some of the servos, wires, sensors and metal parts exposed. This was fine for early prototypes being used directly by researchers, but this was not sufficient to give to parents and teachers to work with children in schools and homes. The K5 robot was designed to conceal as many parts of the robot at possible to reduce potential for getting fingers caught in gaps and make the robot more robust. The hands of the robot were designed to conceal the sensors behind a silicon skin which both protected the sensors and gave the hands a nice feel. The arm and neck joints of the robot were covered with bellows (flexible covers) that were CAD designed and 3d printed using NinjaFlex a thermoplastic polyurethane (TPU) material[2]. The addition of all these features serves to improve the reliability of the robot and also add flexibility to enable the robot to engage in more activities with the children.

In 2016 a number of significant upgrades were made to the K5 robot greatly improving the functionality of the robot, these upgrades included both hardware and software, but all were driven by the user requirements of assisting children with ASC. These changes are what constitute the K5.5 robot. An RFID reader was integrated into the robot to enable it to read RFID tags. RFID technology is ideal for the Kaspar robot because it is small, inexpensive and reliable. The RFID reader is currently used to change the games on the robot without having to select it on the PC controlling the robot. However, we plan to use this technology in the near future for Kaspar to recognise different RFID tagged toys and design games around these toys for the children, opening up a range of semi-autonomous games that could be robustly implemented with the robot. Further to the RFID reader, another addition to the K5 robot was magnetic hands that would allow the robot to hold objects that have been fitted with magnets. Recently this feature has been used to great effect for assisting children with ASC that have difficulty with food. A number of magnetic accessories have been developed for Kaspar to hold, including a spoon, fork and toothbrush. Using these accessories Kaspar can simulate eating and personal hygiene to encourage the children to eat and brush their teeth. Initial feedback from a nursery school using the K5.5 robot with these features is very positive and indicates that these features could potentially be used to great effect.

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[2] https://ninjatek.com/

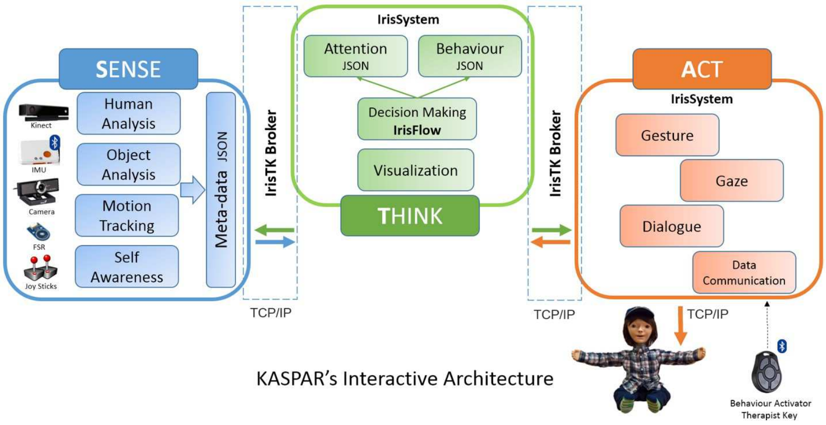

Fig. 2: The Kaspar's interactive architecture for semi-autonomous interaction.

3 Moving towards greater robot autonomy in robot-assisted therapy

Robot-assisted therapy has been successfully used to assist children with ASC, but very often with the robot being partially or fully controlled remotely by an adult operator, usually a researcher, therapist, teacher or parent. This method allows the therapist to administer a personalised intervention and run a therapy session in a customised child-centred manner and work towards high-level goals such as developing the child's social skills, without requiring the development of sophisticated robot control systems. However, this method requires the therapists to divide their attention between the robot and child to ensure that the robot is responding appropriately to the child's behaviour. Sharing attention between the robot and the child whilst evaluating the progress of child in relation to predefined therapeutic objectives, increases the cognitive workload on the therapist and makes this method unsustainable for long-term interactions [18]. To lighten the cognitive load on therapist and to provide a consistent therapeutic experience, it is essential to increase the level of the robot's autonomy and enable the robot to perform autonomous behaviours when interacting with a child. However, due to the limitations of sensing technologies and computing techniques, as well as the ethical issues regarding the use of robots with children with special needs, the development of a fully autonomous robot is currently unrealistic. There are strong indications that the deployment of a fully autonomous system is not desirable for interaction with vulnerable children [19]. Thus, for the above reasons, the development and deployment of a *semi-autonomous* robot seems to be the most suitable solution.

In a semi-autonomous child-robot interaction, the robot has some degree of autonomy and only requires partial control by a human operator which reduces the cognitive workload of the operator. However, the therapists must still retain control over the robot's high level behaviours to ensure the learning or therapeutic objectives are being met. Thus, the aim is not to replace therapist with a robot but provide the therapist with an effective tool to deliver an effective treatment to the children with ASC.

In order to integrate some semi-autonomous features into the most recent generation of the Kaspar robot (K5.5), we have been developing an interactive Sense-Think-Act architecture (shown in Fig. 2) which has been employed to control particular

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[2] https://youtu.be/ujlas3J0kcg

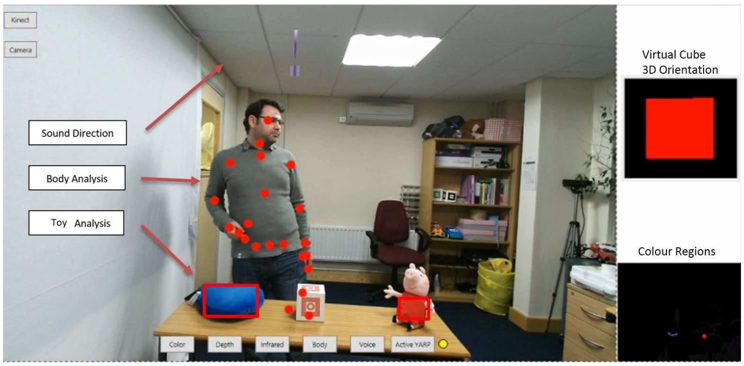

Fig. 3: The visualisation of high-level features extracted features.

aspects of Kaspar's behaviour in a semi-autonomous manner. The architecture has three main layers which perform perception, decision making and motor control for the robot. The layers pass data through a TCP/IP connection called IrisTK broker. Because the primary objective in our current studies for the BabyRobot project is to help teach children with ASC about Visual Perspective Taking (VPT), we have developed a number of games with the Kaspar robot [6] that aim to help them understand and learn about VPT by using a number of toys that the children can show to Kaspar and see what Kaspar sees via a screen that displays what is visible from the robot's eyes. Enabling a semi-autonomous child-robot interaction in these scenarios, requires Kaspar to perceive humans, objects and the environment, then triggers behaviour upon request accordingly. For this reason, the sense layers of the interactive system extracts the high-level features and social events (shown in Fig. 3) in the robot's field of view and controls the robots behaviour based on the predefined rules. More details about the system's performance and its implementation can be found in [20].

4 Conclusions

Since the initial development of Kaspar in 2005 many lessons have been learnt about developing humanoid robots for children with ASC. The primary factors that affect the potential success of a robot for this application area are as follows:

- User focused - Features must be driven by therapeutic and educational objectives rather than by technology. Technology is merely a facilitator and should be used to fulfill the needs of the users whether this is to reduce the cognitive load on the operator or facilitate a particular type of interaction for the child.
- Usability - Regardless of the developments in hardware, software or scenarios, they all need to be practical and usable, otherwise they will never work in a real world setting.
- Reliability - Reliability is as important as other aspects of the system to instil confidence in the users. Unless a system is reliable it will not be perceived well by any of its users and will be doomed to fail. This is why it is important to integrate reliable robust technology that will consistently work even in noisy and dynamic environment such as a school or home.
- Safety - Safety is paramount to any system being used in real-world contexts, so attention has been paid in the development of Kaspar to avoid a range of possible hazards. When being used by parents or teachers themselves, we ensured that they

were aware of the research-prototype nature of the robot and potential health and safety concerns (this includes a list of safety instructions that need to be signed by its users, e.g. to keep the robot away from water).

- Affordability - If systems such as Kaspar are ever to become viable to produce on a mass market scale, the systems need to be affordable which has always been a key pillar of Kaspar. Taking this factor into account Kaspar has always been designed on a budget with affordable (often off-the-shelf) components and this design principle will continue.

As can be seen from the iterative development of the Kaspar robot over the last 12 years, technological advancements are enabling more useful and complex scenarios and systems to be developed. The advancements are not only facilitating new games that can assist children learn new skills, but are also making therapeutic robots such as Kaspar more robust. When Kaspar was first developed the ability to track users without attaching devices to them and with reasonable accuracy was not even a possibility. However, new sensing technologies such as the Kinect are not enough on their own. More work and research needs to be conducted in order to fully utilise the benefits of such technologies.

Acknowledgments

This work has been partially funded by the BabyRobot project supported by the EU Horizon 2020 Programme under grant 687831.

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