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INVITED TALK

Henrik Hautop Lund · Martin Dam Pedersen
Richard Beck

Modular robotic tiles: experiments for children with autism

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Abstract We developed a modular robotic tile and a system composed of a number of these modular robotic tiles. The system composed of the modular robotic tiles engages the user in physical activities, e.g., physiotherapy, sports, fitness, and entertainment. The modular robotic tiles motivate the user to perform physical activities by providing immediate feedback based upon their physical interaction with the system. With the modular robotic tiles, the user is able to make new physical set-ups within less than a minute. The tiles are applicable for different forms of physical activities (e.g., therapeutic rehabilitation), and with the proper radio communication mechanism they may give unique possibilities for documentation of the physical activity (e.g., therapeutic treatment). A major point of concern in modular robotics is the connection mechanism, so we investigated different solutions for the connection between the modules, and outline their pros and cons for utilizing modules with different connection mechanisms as different kinds of playware. This kind of playware is highly motivating because of its immediate feedback and fun, interesting games.

Key words Modular robotics · Human–robot interaction · Playware · Therapy

1 Introduction

Processing in electronic artifacts is traditionally based on central control. This is the case in VCRs, televisions, mobile phones, industrial robots, toy robots, etc. In such cases, the device is controlled by an electronic system with a central control. If just a small part of the central control breaks down, the whole system/device may break down. These modular robotic tiles challenge traditional central control, and allow processing to be distributed among a number of processing units that can be connected together to form a larger, collective system. The individual unit is self-contained, including processing capabilities, communication capabilities, and batteries. A system comprising a number of such units allows the end user to define the physical shape and functionality of the artifact and to interact with the artifact.

By the enumeration of neighbors, an individual unit is able to communicate with other specified units in the system. The detection of neighbors and the overall structure can be done automatically by the system itself at run-time, which facilitates easy modification of the physical form by any user.

User interaction and the capacity for constructing electronic artifacts are enhanced by particular processing methods. The modular robotic tiles allow construction of both the physical shape and functionality through the physical construction with no necessary need for a personal computer or similar external programming station or monitor.

We can make the tiles into *playware*[1] by making games to run as software on a system composed of modular robotic tiles. Games can adjust themselves to fit any physical configuration made by the user. Each game can be adjusted to fit particular user groups and levels, such as individual therapeutic patients, fitness trainees, etc.

The modular robotic tiles differ from other interactive surfaces and games surfaces in their modularity, the possibility for users to modify the physical shape, the easy setup, the possibility of the exclusion of an external host computer, the self-contained energy source, the wireless communication (local and global), and the individual games.

For instance, we have used modular robotic tiles for the rehabilitation of cardiac patients (at the hospital Sygehus Fyn Svendborg and at the Rehabilitation Centre Odense). For cardiac patients, the games on the tiles may result in a rise in pulse rate to appropriate levels. Physiotherapist Tonny Jaeger Pedersen, from the Sygehus Fyn Svendborg Hospital, says: "the individual training, which the intelligent

H.H. Lund (✉) · M. Dam Pedersen · R. Beck
Centre for Playware, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
e-mail: Henrik.Hautop.Lund@gmail.com

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tiles allow for, is really an advantage. Motivation and competition is the fuel which make us do the most – regardless of whether being healthy or a patient."[2,3] Other games may also be used: for instance, for knee-operated exercises that demand the correct movement of the knee and the correct force exerted to play the game, for elderly play, and games that support balance training, etc.

However, the use of modular robotic playware platforms may be much broader, and with properly designed tiles similar to the ones mentioned above may be used for cognitive rehabilitation. We can imagine that cognitive tasks may be implemented on the modular robotic tiles, and feedback (light and sound) given to the user based upon the user's performance in the cognitive tasks. Games of different levels may challenge users with different cognitive capabilities, and the games may be easily adjustable to different capabilities. This may, for example, be exemplified by imitation games on the system of modular robotic tiles for autistic children. In order to introduce modular robotic tiles in this field, we will start with a simple example of implementation.

In order to develop such modular robotic tiles, there are a number of design issues for modular robotic artifacts to be considered. These design issues include selection of the connection mechanism, energy use, the sensing and actuation system, and centralized versus distributed processing. Regarding the connection mechanism, one may provide (i) easy attachment/detachment, e.g., through magnetic connectors, or (ii) strong and robust connections, e.g., through mechanical locking systems like hooks or as a puzzle (which is the case in the newest version of our tiles). The choice will depend on the use scenario for the modular robotic artifact. The energy use can be (i) centralized with one power source for the whole system, or (ii) decentralized, where each module has its own power source. The processing can also be either centralized or decentralized. In the centralized case, a host computer can control all the modules (e.g., through a radio link), and in the decentralized case, the processing takes place in each individual module, which may communicate with its neighbors (e.g., using infrared communication) or between clusters of modules (e.g., using radio communication).

Fig. 1. One of the children with autism playing with the modular robotic tiles

Fig. 2. The modular robotic tiles from Entertainment Robotics

2 Modular robotic tiles

Our system is composed of a number of modular robotic tiles which can attach to each other to form the overall system. Each tile has a quadratic shape measuring 300 mm × 300 mm × 33 mm (see Figs. 1 and 2), and is molded in polyurethane. In the center, there is a circular dent of diameter 200 mm which has a raised platform of diameter 63 mm in the center. The dent can contain the circular printed circuit board (PCB) and the electronic components mounted on the PCB. At the center of each of the four sides of the quadratic shape, there is a small tube of diameter 16 mm through which infrared (IR) signals can be emitted and received (from neighboring blocks). Small magnets are placed on each side of the tiles. The magnets on the back provide the opportunity for a tile to be mounted on a magnetic surface (e.g., a wall), and the magnets on the sides provide opportunities for the tiles to attach to each other. The magnets ensure that when two tiles are put together they will become aligned by the magnetic forces, which is important for ensuring that the tubes on the two tiles are aligned for IR communication. On one side of the tile there is also a small hole for a charging plug (used for connecting a battery charger and for reset).

There is a small groove on the top of the wall of the circular dent, so a circular cover of diameter 210 mm can be mounted on top of the dent. The cover is made from a circular transparent Plexiglass satinice® plate with a polyurethane circle in the center.

A force-sensitive resistor (FSR) is mounted as a sensor in the center of the raised platform underneath the circular cover. This allows analogue measurements of the force exerted on the top of the cover.

There are three NIMH AA batteries (rechargeable batteries) on top of the PCB. A 2-axis accelerometer (5G) is mounted to detect, e.g., the horizontal or vertical placement of the block. Eight RGB light-emitting diodes (LED SMD 1206) are mounted, with equal spacing in between each of them, on a circle on the PCB, so that they can light up underneath the transparent Satin Ice circle.

On the PCB, there are connectors to mount an XBee radio communication add-on PCB, including the Max-Stream XBee radio communication chip

The modular robotic tiles can easily be set up on the floor or wall within one minute. The modular robotic tiles can simply attach to each other with magnets, and there are no wires. The modular robotic tiles can register whether they are placed horizontally or vertically, and by themselves they can make the software games behave accordingly.

Also, the modular robotic tiles can be put together in groups, and the groups of tiles may communicate with each other by wireless (radio). For instance, one game may be distributed on a group of blocks on the floor and a group of blocks on the wall, thus demanding that the user should interact physically with both the floor and the wall.

3 Related work

Previously, we developed the robotic building block concept exemplified, e.g., with the I-BLOCKS for play in hospitals and developing countries,[4,5] and interactive playware playgrounds.[1] The robotic building block concept for the playware playgrounds came from a longer design process started in 2001, and that for the I-BLOCKS was started in the late 1990s. As an example, the neural I-BLOCKS[6] can be viewed as a modular entertainment system that allows anyone to create neural networks by physically building with the modular robotic building blocks, I-BLOCKS. This use of modular robotics for entertainment and learning with the I-BLOCKS is used in Africa to allow nonexpert users to become developers of novel intelligent robotics in schools, hospitals, orphanages, and science parks.

The modular robotic approach was further elaborated in the playware playgrounds.[1] These intelligent playgrounds are developed as a set of modular robotic tiles that allows implementation of physical computer games in the playgrounds, which are now installed in numerous schools, kindergartens, and youth clubs in the city of Odense in Denmark. Some work shows how implementations with neural networks may allow the playground to recognize the children's behavior in the playground and adapt the games at run-time to the individual child.

The modular robotic approach for entertainment is used in this article to allow the development of novel robotic therapy tiles not only for the rehabilitation of cardiac patients, but also for autistic children in an entertaining way.

In general, the modular robotic approach to entertainment robots is investigating how the public can understand and use robotics by introducing robotics as entertainment and play in the daily life and environment of people. This happens through the combination of modern artificial intelligence, modular robotics and entertainment to provide novel opportunities in play, rehabilitation, sport, music, teaching, Third-World development, etc. It is believed that this approach may provide nonexpert users with easy access to the technology in a playful and motivating way.

Not many other systems for large-scale physical manipulation are truly modular and distributed. An exception is the floating tiles prototypes by Marti and co-workers.[7] Most other systems are either small in scale (e.g., hands-on constructionist robot building kits such as Topobo[8], System Blocks,[9] and few other similar systems), not for end-user physical reconfiguration (e.g., Z-tiles,[10] smart-floor), or not truly modular with distributed processing.

4 Modular robotic tiles for children with autism

In general, children with autism may have problems with social/emotional relationships, problems with communication, problems with their consciousness of their surroundings, motor problems, and possibly cognitive problems. Moreover, many of these children also have other diagnoses such as ADHD (attention-deficit hyperactivity disorder). One of the aspects of these handicaps is that the children have serious problems with being creative, and they have problems playing on their own without guidance on how to play. However, our first pilot tests with such children showed some very interesting behavior. The observations done by the therapist from the autism home Bihuset told us that the children's behavior with the tiles was comparable to their normal behavior in everyday life. Since the children's behavior seems very much connected to their diagnosis, this gave us an indication of the possibility of using the tiles as a supplementary tool to support the therapists in diagnosing the children. Then the research question becomes: can data collected from experiments with the modular robotic tiles be used to recognize specific behaviors or to categorize users? If so (i.e., if it is possible to recognize what problems the individual child has), it could even become possible to adapt the application to fit the child, and thereby make the play more interesting.

5 Game implementation

For this experiment, we used a set of 15 tiles and the game called *color-mix*. The basic idea is to mix colors in different ways, depending on how the tiles are assembled. Three tiles are predefined the as source tiles, and have the colors red, green, and blue. The other 12 tiles are normal tiles, with the property that they can change their colors according to their local neighborhood. If a normal tile is connected to a red source tile, the normal tile will become red just like its neighbor but with a lower intensity. The source tiles never change their color. If a blue source tile is also connected to a normal tile at the same time as a red source tile, the normal tile will blend the two colors to become a purple tile. A normal tile should always light up with a lower

Fig. 3. The data collection and data analysis scheme

Table 1. Children, diagnoses, and number of tests performed

Name	Diagnosis	Tests
Nik	Infantile	5
Anne	Infantile	3
Dan	Infantile	2
Zofus	Atypical	3
Josef	Atypical	2
Ole	Asperger syndrome	3
Marck	Other developmental disorder	2

intensity than its neighbors' color intensity, which makes the color spreading from a source tile decrease as the distance to a source tile increases.

For the color-mix game, we used a distributed control approach, which is fairly straightforward since every tile is equipped with both communication and computation capabilities. The tiles can be moved around and connected to each other in any configuration. In this distributed environment, it is very easy to make local changes based on the local environment. A tile can easily read the states of neighboring tiles, and thereby change its own state according to some local rules. By not having a central server to administer the data flow between tiles, the stability of the application will not depend on the reachability of a master-tile. Simple rules based on the local environment are easily implemented, and the software on the individual tiles can be kept simple. Other advantages are that there is no need for instructions to the users on how to use/control a master-tile, and the possibility of extending the application by adding simple new rules to one or more of the tiles. Also, the distributed control facilitates the emergence of new behaviors when different rules are influencing each other. It is not always possible to predict what can emerge from such a system. This could be a drawback to an application if it was critical to the behavior of the whole system that the user always gets what they expect. In a performance application, emergence is actually an advantage, because it would create unexpected results from the user's point of view, and thereby tease their curiosity to continue using the application. A major drawback with this kind of distributed control is that there is no easy option to log events in the system. Hence, we added radio modules to the tiles to allow them to send logged data to a host computer, which was used exclusively for data collection (Fig. 3).

6 Experimental protocol

The experiments were performed at the institution Bihuset. Bihuset is both a residential home for children with autism, and a respite home for relieving parents with children with autism for a day or two. The two different functions are located at two different addresses. (Jørgen Haubroe Andreasen is the head therapist at the residential home, and Inga is the head therapist at the respite center.) The first experiments were conducted at the residential home with two children named Nik and Ole. These two children performed very differently with the tiles, and it was very interesting to the therapist Jørgen that in both cases the children's normal behaviors were directly reflected in their use of the tiles.

The rest of the experiments were carried out in the institution's respite center. The main reason for this was the need for children who were suitable and present for the experiments. The children at the residential home are much more handicapped than the ones coming to the respite center, and therefore the children from the respite center seemed more suitable for the initial experiments. Because of vacations among both the children and the staff, there were some difficulties in following the original experiment plan. The plan was adjusted, and we tried to carry out as many experiments as possible. Unfortunately, it was not possible to carry out experiments with enough children to create statistically reliable results. Table 1 shows the test subjects (the name of each child has been changed to protect their anonymity).

The following plan was carried out in each of the experiments. The duration of each experiment was 10 min.

- Each experiment was documented on video.
- A computer collected data from each experiment.
- When more than one experiment was performed with the same child, the environment did not change significantly.
- The children were shown the tiles very briefly, and told to play with them for 10 min. They were told to do whatever they felt like.
- When the timing had started, the children could not get any help from the adults.
- The adults could only interfere with the experiment if the child had lost interest in the tiles completely. In that case, the only thing the adult is allowed to do is to ask the child to use the tiles again.
- When the 10 min were over, the adult stopped the child from playing, and also stopped the video and the computer logging.

7 Data analysis

After all the experiments were finished, the data, which were collected automatically, were analyzed off-line. First a list of different criteria was compiled by watching the recorded videos. These criteria were created in such a way that each child would get a score for each criterion when the collected data were analyzed. These analyses could then be used to differentiate the individual users from each other by looking at the result from each criteria analysis. In what follows only individuals will be examined, and not groups of individuals. If the number of users had been higher, it would also have been possible to see if there were any data that could differentiate groups from each other. The children could have been grouped by cognitive level or other categories involving their handicap. The categories used were assessed by the number of tiles used during the experiment. These were:

1. The number of clusters created by the user. A cluster is defined as 2 or more tiles assembled.
2. The number of pressed tiles.
3. Removing a tile and placing it in exactly the same position immediately afterward.
4. Removing a tile and placing it in a new position immediately afterward.
5. The average cluster size.
6. After the complete assembly of all tiles in one cluster, the cluster is destroyed again. A cluster is only considered to have been destroyed if 2 or more tiles are removed from it.
7. The cluster shapes in the clusters created by the users (line, rectangle, quadratic, advanced).
8. The speed with which the user assembled the tiles.
9. The average intensity of the red, green, and blue LEDs on tiles moved.
10. The average number of source tiles per cluster.

Some of the categories can be expanded, so that category number 2 becomes two categories (average number and maximum number), number 8 becomes three categories (rectangle, quadratic, other) and number 10 becomes three categories (one for each color), so there will be a total of 16 categories.

For each experiment, the score in these categories can be collected *automatically* during the play with the modular robotic tiles. The score for each category can be normalized and fed into a simple, feed-forward neural network (C1 . . . C16 in Fig. 4).

We feed the data into the feed-forward neural network in order to understand whether possible differences in the criteria scores can be used to recognize any specific behavior pattern, or even to try to recognize the individual child. By recognizing an individual during play, it may become possible to adjust the activity on the tiles according to the individual's needs.

Each experiment was divided into four phases to create more examples. The first phase from each experiment was removed from the examples as they are very different from the rest of the experimental phases. This gave a total of three examples per experiment, and with a total of 20 experiments this is 60 examples in total.

The training set contained 3 experiments with Nik, 2 with Anne, 1 with Dan, 2 with Zofus, 1 with Josef, 2 with Ole, and 1 with Mark. This is a total of 36 examples, but only 35 where used since one of them contained nothing but 0 scores. The test set contained 2 experiments with Nik and 1 experiment with each of the other children. This is a total of 24 examples, but only 23 where used for the same reason as above. Each example includes all 16 criteria scores as input, and 7 output neurons to indicate each of the individuals. The neural network can be seen in Fig. 4.

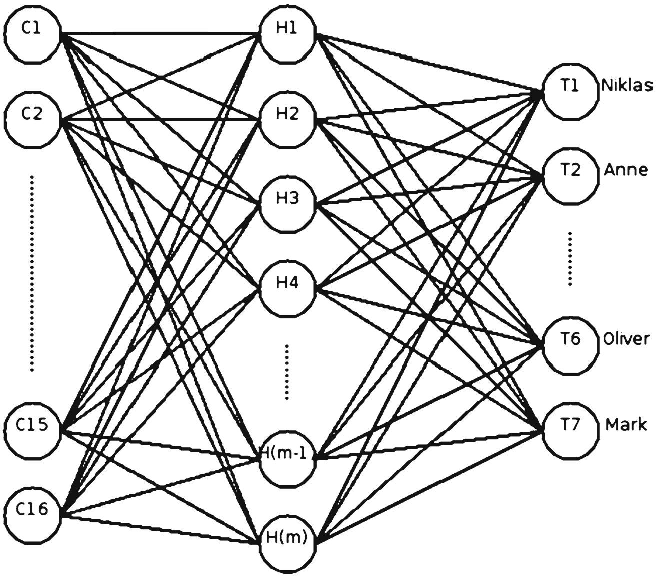

Fig. 4. The neural network

The number of hidden neurons was selected to be 9, since fewer showed a tendency to make the network converge too fast, and with more hidden neurons the network had problems converging at all.

The results can be seen in Table 2, which shows the value for each target neuron with the test set. The maximum value for each result is shown in bold face. The expected result for Nik would be that the first output neuron should be the highest, for Anne it should be the second, for Dan the third, etc. If all the classifications were correct we should see a diagonal of bold numbers.

It can be seen that the network makes a correct classification in 19 of 23 examples. This is an 88% correct classification of the children. The examples that do not get correctly classified are all one example out of three from the same experiment, and the two remaining examples from that same experiment are correctly classified. So post-processing into one result for each experiment would then give a 100% correct classification. These results should be treated with caution because of the very limited number of examples available. To create a statistically reliable result there should be many more examples in the test set.

8 Discussion and conclusion

It is important to take these experiments for what they are and nothing more. We were able to use a technological development in an initial pilot study. At this time, it was not possible for us to undertake a complete scientific study with the autistic children as the user group, which means that we can do no statistical tests to verify the indications given

Table 2. The neural network output (in boldface) for each experiment

Name	T1	T2	T3	T4	T5	T6	T7
Nik	**1,000**	0,000	0,000	0,000	0,001	0,000	0,000
Nik	0,006	0,000	0,001	0,001	0,000	**0,880**	0,000
Nik	**1,000**	0,000	0,001	0,000	0,002	0,000	0,000
Nik	**0,449**	0,000	0,025	0,000	0,000	0,017	0,000
Nik	**0,878**	0,000	0,476	0,000	0,000	0,025	0,000
Nik	**0,961**	0,000	0,132	0,000	0,000	0,002	0,000
Anne	0,000	**0,989**	0,003	0,000	0,004	0,000	0,235
Anne	0,004	**0,999**	0,010	0,000	0,002	0,000	0,000
Anne	**0,999**	0,000	0,000	0,000	0,005	0,000	0,000
Dan	0,001	0,002	**0,989**	0,000	0,006	0,000	0,000
Dan	0,001	0,002	**0,989**	0,000	0,006	0,000	0,000
Zofus	0,000	0,000	0,000	**0,997**	0,000	0,000	0,000
Zofus	0,000	0,000	0,000	**0,995**	0,000	0,000	0,000
Zofus	0,000	0,000	0,000	**0,991**	0,000	0,000	0,000
Josef	0,000	0,042	0,000	0,000	**0,495**	0,000	0,330
Josef	0,026	0,000	0,002	0,000	**0,947**	0,000	0,000
Josef	0,001	0,333	0,000	0,000	**0,689**	0,000	0,006
Ole	0,002	**0,873**	0,001	0,000	0,000	0,000	0,016
Ole	0,176	0,000	0,000	0,001	0,000	**0,431**	0,000
Ole	0,002	0,000	0,000	0,008	0,000	**0,999**	0,000
Marck	0,000	0,004	0,001	0,001	0,000	0,003	**1,000**
Marck	0,000	0,023	0,002	0,000	0,007	0,002	**0,985**
Marck	0,001	0,000	0,011	0,000	0,000	**0,651**	0,122

above. It is important to be aware of this fact. We were not able to perform large-scale tests due to material constraints (we only produced 100 tiles), time constraints, and limited access to the user group.

Nevertheless, we find the *indications* interesting, and worth further discussion, development, and tests. The indications with the small test group are that whereas the children with autism may not produce creative performances with the modular robotic tiles, they will, however, build and interact with the tiles in a very individual, stereotypic manner. This may come as no surprise, but the interesting indication is that the novel technology may be able to *automatically* recognize this individual behavior. Indeed, with post-processing, the artificial neural network used in this study was able to make a 100% correct classification of the 7 children with autism from the pilot study (and 88% correct classifications without post-processing).

It will be very interesting to use these indications to investigate whether such modular robotic tiles or similar playware can be used as a supplementary tool in the diagnosis process for children with autism. Typically, many tools are used for the diagnosis, and the one presented here should be viewed only as a supplement to these other tools. However, if the automatic recognition of individual behavior (individual diagnosis) is also possible for larger test groups, then it may become an interesting tool to support and supplement the other diagnosis tools.

The pilot study also gave an indication that this particular user group was able to interact with the modular robotic tiles. Therefore, we are initiating collaboration with J. Nadel's group at the Hôpital de la Salpêtrière in Paris to study how to promote emotionally positive social interaction through physical action, specifically in imitative scenarios for children with autistic spectrum disorder, with large user groups, and with test groups.

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