# A Creative Solution of Distributed Modular Systems for Building Ubiquitous Heterogeneous Robotic Applications

**Trung Dung Ngo** and **Henrik Hautop Lund**
Adaptronics group
Maesrk Mc-Kinney Moller Institute of Production Technology
University of Southern Denmark, Campusvej 55, 5230, Odense M. Denmark
Tel: (+45) 65 50 35 75 Fax: (+45) 66 15 76 97
E-mail: {dungnt,hhl}@mip.sdu.dk

**Abstract**: Employing knowledge of adaptive possibilities of agents in multi-agents system, we have explored new aspects of distributed modular systems for building ubiquitous heterogeneous robotic systems using intelligent building blocks (I-BLOCKS) [1] as reconfigurable modules. This paper describes early technological approaches related to technical design, experimental developments and evaluation of adaptive processing and information interaction among I-BLOCKS allowing users to easily develop modular robotic systems. The processing technology presented in this paper is embedded inside each DUPLO[1] brick by microprocessor as well as selected sensors and actuators in addition. Behaviors of an I-BLOCKS modular structure are defined by the internal processing functionality of each I-Block in such structure and communication capacities between I-BLOCKS. Users of the I-BLOCKS system can easily do "*programming by building*" and thereby create specific functionalities of a modular robotic structure of intelligent artefacts without the need to learn and use traditional programming language. From investigating different effects of modern artificial intelligence, I-BLOCKS we have developed might possibly contain potential possibilities for developing modular robotic system with different types of morphology, functionality and behavior. To assess these potential I-BLOCKS possibilities, the paper presents a limited range of different experimental scenarios in which I-BLOCKS have been used to set-up reconfigurable modular robots. The paper also reports briefly about earlier experiments of I-BLOCKS created on users' natural inspiration by a just defined concept of modular artefacts.

Ambient intelligence, intelligent building blocks, tangible programming, cooperative autonomous vehicles, behavior-based robotics, disappearing and invisible computer, learning by playing

## 1. INTRODUCTION

In recent years there has been in increasing interest in heterogeneous robotic applications in ubiquitous environments. The heterogeneous robotic system is an individual robot that constructed by heterogeneous components associated together or a group of cooperative robots that have not the same characteristics but they will compensate their characteristics to the others when cooperating. However, to adapt with changes of operating environments, the robot or group of robots should be change its characteristics though changing morphology or operating manner. Fundamentally, such applications require a solution of building robotic systems that can work in different operating environments

Until now, many robotic researchers are still looking for an approach to a general solution for ubiquitous robotic applications. In this paper we describe technologically innovative implementation built up from intelligent building blocks to explore potential solutions for heterogeneous robotic applications in ubiquitous environments. An essential property in our work is the development of distributed modules of intelligent building blocks in which each building block acts as an agent needs to be centered on the individual while behaviors of building blocks structure as multi agents system is based on adaptive interaction of building blocks in such system. In vision of robotic systems, each building block is a mechanical joint that can physically link with the other joints via mechanical connectors. Further, it acts as a sensing or actuating module in order to make a robotic system in combination. Each module itself obtains individual processing power that change behavior of the robotic system if it is an actuation module or interact with surrounding environment if it is a sensing module. Therefore, the robotic system made by combination of sensing and actuation modules might behave in a specific way decided by user, depended on internal processing method of modular structure and interactive capabilities with surrounding environment.

By implementing a series of robotic experiments that can be made and distributed in ubiquitous environments we suggest a new specific kind of devices to explore the design solutions for intelligent robotic systems, both of hardware architecture and software implementation. Further, we discuss possibilities discovered by embedded mobile agents model though embodiment of I-BLOCKS modular system, explaining how each building block as an agent enables communication, interaction and cooperative operation in robotic structures of different building blocks

[1] LEGO and DUPLO are trademarks of LEGO System A/S

## 2. INTELLIGENT BUILDING BLOCKS

We have developed a series of intelligent building blocks [1] in the first generation in which each I-BLOCK itself contains internal processing and communication capacities. In our implementation electronic control board is housed inside LEGO DUPLO bricks, which contains a PIC16F1876 28-pins 8 bits CMOS Flash micro-controller for processing. Each I-Block provides capacity of bi-directional serial communication via four physical connectors, two male connectors on the top and two female ones under the bottom. Energy power from a battery building block is supported via connectors on the top-part of bricks, where the connectors have been distributed to 8 studs on the top and in the bottom-part at 4 corners of bricks.
When building blocks are physically connected together in specified order for a physical construction, they can communicate with each other via connection(s) of half-duplex communication. In the sending building block, packages of data are sent via at least one of four connections while receiving building block is received by attached communication connection(s). In typical setup, each building block will receive input from its neighbours on communication channels, processing this input data, and then sending the output data to communication channels as output. A construction of such building blocks will have specific functionality defined by the physical construction, input of each building block, internal processing of the individual one, and communication schemes. If input, processing, and communication are predefined, the user of such a system can decide the functionality of the system by manipulating the physical structure.

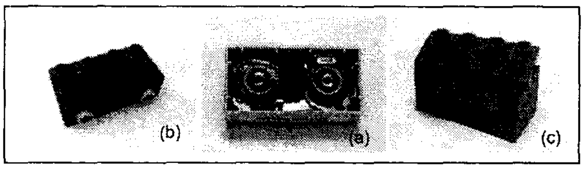


Fig.1. (a): A CPU building blocks including internal processor and communication channels. (b): Input building block that contains two LDR sensors as an input device in addition of CPU I-BLOCKS to allow measure light density. (c): Output building block that contain a servo motor allowing the top segment to turn in steps as a output device.
In order to make a I-BLOCK interact with other I-BLOCKS or inhabited environment, we have developed a lot of different types of I-BLOCKS that all have the same building technology of processing and communication capacities but numerous number of them are extended with the addition of sensors as *input building block* and actuators as *output building block* in the first generation. Input building blocks include standard building blocks adding LDR sensor, microphone, potentiometer, switches while output building blocks include standard building blocks combining with servo motor, DC motor, LEDs, sound generator, etc.
To evolve inter-interaction between building blocks or interaction of bricks in inhabited environment, the second generation of building blocks including multi-infrared sensors (M-IR), ultrasound sensor (US), accelerometer and radio frequency (ACC-RF), have been developed. The development arises much more capabilities of interactive communication between neighborhood structure of building blocks so that such structures are now able to communicate not only via physical connection of maximum of four building blocks on the top and the bottom connected together but also by using wireless communication among many of building blocks as well as structures of building blocks (e.g. up to 128 wireless channels if RF building blocks are used).
In the first generation of I-BLOCKS, basically different kinds of processing in the I-BLOCKS such as making the I-BLOCKS become arithmetic blocks, behavioral blocks neural blocks were implemented. However, the I-BLOCKS of the first generation was limited in specific research fields because of their communication capacities as well as individual functionality of building blocks that are able to interact with human beings and environmental surroundings. In order to extend variety of application of I-BLOCKS in different fields, which one can discovered from modern AI principles such as biologically inspired systems, agent-based computing, complex system, etc, the second generation has been developed to partly fill up.

## 3. BEHAVIOUR-BASED ROBOTICS

Behavior-based robot is a research branch of robotics that does not use an internal model of environment. For instance, there is no predetermined programming in the robot that may be a mobile robot, but all the information is gleaned from input of the robot's sensors. The robot uses that information to react with the changes in its environment.
In the implementation, we constructed a LEGO mobile robot for purpose of tracking the way between corridors. LEGO materials are used to build the robot in which two DC motors are main factors to control behavior of the robot. To control two motors, two LEGO motor building blocks are necessarily implemented to connect. The building blocks are setup to attach the LEGO motor connectors to analog port of the PIC that is usually used for analog communications.

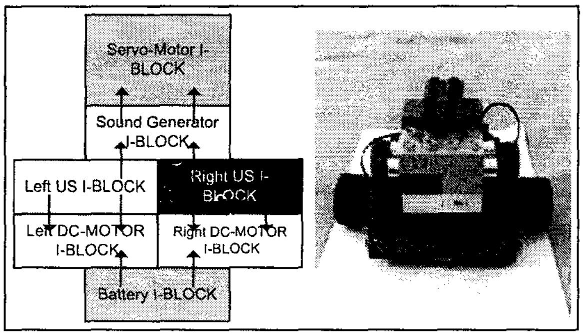


Fig. 2. Left: Block diagram of the modular structure of the I-BLOCKS for Behavior-Based Robot. Right: Real robot "Corridor Tracker"

In order to track the way between wall corridors, a principle of ultrasonic ranging finder that is used to estimate the distance from mobile object to opposite obstacles has been recognized as good solution in the cases. A couple of US building blocks are directly assembled to motor I-BLOCKS in the way that is perpendicular to forward direction of the mobile robot. The operation of US I-BLOCKS is to estimate the distance from the robot to the corridor wall and transfer the result to Motor I-BLOCKS via physical connection(s). To calculate the instantaneous distance, the US building block has to contain a pair of transmitting and receiving ultrasonic sensors controlled by a processor in which the processor will generate a range of amplified sonic signals (sonic burst) from starting trigger pulse before sending via transmitter while the receiver is waiting for receive echoes. The distance will be proportional to time period of traveling of signal in ratio of ultrasonic speed in air (approx. 346m/S).

Developed by the concept of *"behavior-based robots"*, US I-BLOCKS works as sensor modules that interact with environmental surroundings to support input data and Motor I-BLOCKS operate as actuator modules that control behavior of the robot. In particular, due to homogeneous characteristics of the same type of I-BLOCKS, Motor I-BLOCKS uses the digitalized values measured the distance from the robot to the corridor wall by US-BLOCKS where the values is within a range of 255 scales (one byte). To raise exciting of scientific meaning for the experiment, a sound generator I-BLOCKS and a servo motor I-BLOCKS are attached under the bottom and on the top of the module structure, respectively. The sound generator will generate sound in different frequencies while the servo motor will present steps of rotating direction, depended on the input value sent out by the two US I-BLOCKS. The I-BLOCKS will keep a stable state when the robot goes straight but its states will adaptively change when robot turns left of right at the corner, expressing though higher or lower frequency of sound and arrow direction that show a truly going way of the robot. The structure of connected building blocks and the "corridor tracker" robot are represented in the figure 2.

## 4. AUTONOMOUS COOPERATIVE VEHICLES

Exploration of behavior of mobile robots is traditional research but a focus of cooperative behaviors of mobile robots assembled from distributed functionality modules is rarely interested in. We developed an experiment of mobile robots that can be assembled from specialized I-BLOCKS in order to explore group interactive behavior. To reach the traditional solution of robot technology that is usually developed by different modularity of sensors and actuators, a robot (named as CD-ROBOT) is configured from modular components including sonar ranging finder, radio frequency communication, DC motor driver, accelerometer and extra components. The modular component are connected and controlled by PIC16F876 microprocessor in mainly additional factor as presented in the figure 3.

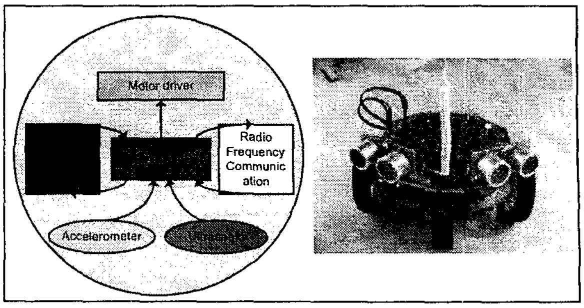


Fig.3. Left: Block diagram of functional modularity, Right: CD-ROBOT designed in LEGO standard

The power supply is inter-connected by 9V batteries put under the electronic main-board. The robot constructed is basically designed in LEGO standard, e.g. LEGO motor, LEGO DUPLO base that can physically connect to any I-BLOCKS for additional sensing and actuation information. There are a lot of open sockets directly connected to PIC, which can be used to not only measure signals but also connect other extra modular components with respect to characteristics of the interactive environment.

Further, to explore grouping behavior of mobile robots, we assembled two LEGO cars by using LEGO materials and specialized I-BLOCKS. Each LEGO car is configured by at least a radio frequency and two motor, a power supply building blocks but they can be attached other building blocks obtaining different functionalities as presented in the figure 4.

On demonstration, we first experimented possibility of automatically tracking a way between corridors using sonar characteristic of measuring distance of all mobile robots. In the CD-ROBOT, based on the design two ultrasound range finders symmetrically attached controlling board at 60, or 90 degrees with forward direction of the robot will real-time measure the two distances from robot to corridor sides. The measured results are transferred to CPU and processed there to control speed of two DC motor. This is really solution of *centralized processing* system in which information all is centralized to a unique processor so that the behavior of robot is controlled by only processor. But, in the other mobile robots assembled by LEGO materials and specialized building blocks, the measured results from US I-BLOCKS are transferred to CPU I-BLOCKS at two different ports. The results are compared at CPU building block as a speed manager and then sent out to Motor I-BLOCKS in order to control speed of motors. This is a solution of *decentralized processing* system (distributed processing) in which information is processed in specific functionality module before transferring to other modules so that the behavior of robot is depended on distributed processing of input information of sensing modules, processing and communication between modules and output information of actuation modules. In both of cases considered, the speed of two LEGO motors are controlled by rules: the robot turns right if the left measured distance is shorter than right one, and vice versa.

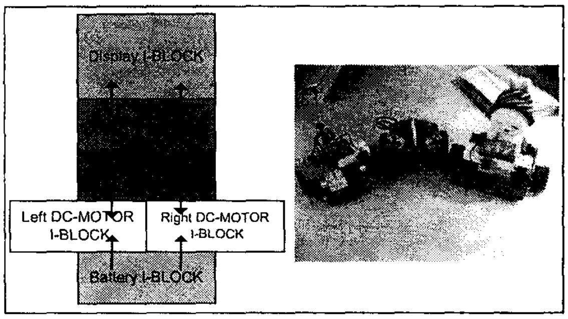


Fig.4. Left: Block diagram of the modular structure of the I-BLOCKS for "slave" robots. Right: Cooperative Autonomous Vehicles

In exploration of grouping behavior of mobile robots, we have been interested in both of technological solutions of local communication and global communication for development of autonomous cooperative vehicles. But, in the paper, only global communication technology is significantly considered. Towards the direction, CD-ROBOT behaves autonomously in interactive relationship with the environment as a master and the other LEGO cars work as slaves. Information collected from behavior of the CD-ROBOT is packed in a data package that is encoded before transferring to the other LEGO cars by radio frequency technology as a global communication system. The information is encoded as left and right controlling commands used to control behavior of the CD-ROBOT. The other LEGO cars will receive that controlling information by using RF I-BLOCKS, transferring to CPU I-BLOCK that works as a decoder to decode the left and right information, sending out left and right ports connected to two Motor I-BLOCKS to control two robot's wheels. A structure of I-BLOCKS can be seen in the figure 4a while the mobile robots can be observed in the figure 4b.
However, any robot may become a master while the others working as slaves by using *"programming by building"* language. This is newly discovered aspect of development for heterogeneous teams of modular mobile robots.

## 5. INVISIBLE HUMAN-ROBOT INTERRACTION

In traditional concept of human-robot interaction, hardware and software is mainly designed to support users an "interface" that is used to interact with the robot. The interface is often computer monitor that human user use command-line, GUI, gesture, etc as input command. Hence, human robot interaction is based on an explicit manner of which the users explicitly request specific actions that should be performed by the robot though its processor (s). However, if we wish the intelligent robotic application exist everywhere in our life, the robot might not keep traditional prototypes as well as interaction method with human users. They should disappear or metamorphose into everyday object so that an interaction between humans and robots will not also express in the traditional way in which user tells directly the robot in a certain abstract instruction of what user experts the robot to do. In contrast, *invisible human robot interaction (In-HRI)* is a behavioral action performed by human users, which is not primarily aimed in interact with a computerized robotic systems but the system understands as input. In the section, we described experimental results of LEGO game in order to explore a new research direction of invisible human-robot interaction.

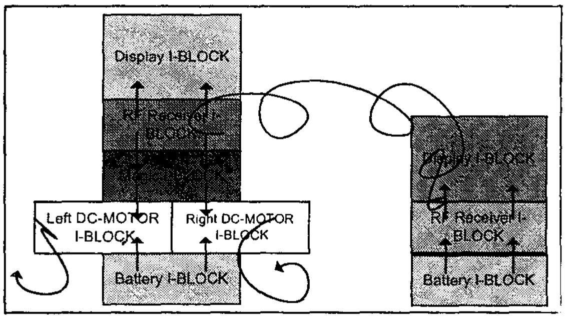


Figure 5: Left: Block diagram for mobile robot. Left: block diagram for remote controller.

For our case studied we implemented a model of LEGO car whose behavior is controlled by a remote controller. However, the impressed viewpoint of the model is that both of the car and remote controller are assembled by toy materials of LEGO bricks with electronic hardware embedded inside (called I-BLOCKS).
The remote controller is a modular structure assembled by a free-battery building block and an ACC+RF I-BLOCK. The structure is powered by a 9V battery regulated to 5V before supporting to the overall systematical circuit. The ACC+RF I-BLOCK holds preprogrammed functionality as RF transmitter with input data collected from instantaneous tilt or sharking of the accelerometer in both direction x and y. The input values captured from accelerometer are depended on the tilting or shaking action of human users in two directions perpendicular to the ground. Before sent out by RF transmitter to RF receiver on the car, the values are encoded by IDs for each direction x or y where values of the x direction will be used to control the forward or backward of the robot while values of x direction will be used to allow the robot to turn left or right. Beside using accelerometer as input, a LDR I-BLOCK including a couple of LDR sensors can be also attached on the RF transmitting I-BLOCK to support values of light density in order to control robot in two directions.

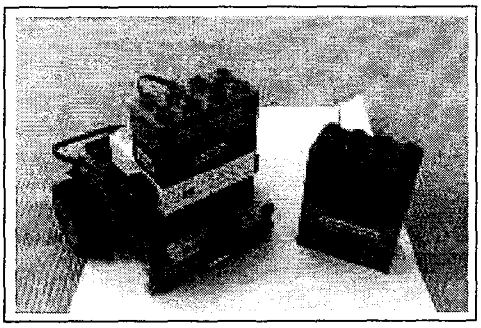

Figure 6: A model of Implicit Human Computer Interaction including a mobile robot and its remote controller

The car body is constructed by LEGO material with two wheels operated by two DC motors. A pair of DC-MOTOR I-BLOCKS is attached on the modular structure in order to control DC motors connected. To support controlling values to control behavior of the car a RF I-BLOCK preprogrammed as a receiver are connected to a CPU I-BLOCK that contains magic processing so that it is properly named MAGIC building block. The MAGIC I-BLOCKS is coded for functionality of a ID decoder that decode the ID to separate the values of forward & backward direction and ones of tuning left & right, a line divider that indicates output ports of the I-BLOCK to two Motor I-BLOCKS and a threshold mechanism that adjusts received values in a regularly operating range of Motor I-BLOCKS. In the structure of different I-BLOCKS, the controlling information signals captured sensors though human user's playing action are implicitly transferred to the controlling structure of the car to control its behavior without user's perception in the interaction.

In exploratory of opposite interaction direction, RF transmitting I-BLOCK of the remote controller is substituted by RF receiving I-BLOCK one and vice versa in modular structure of the system. Furthermore, an US I-BLOCKS are attached on the RF building block on front of the car as a input that can interact with surrounding obstacles and a sound generator are assembled on the RF receiving I-BLOCK of the remote controller that can generate sound when receiving a command from RF I-BLOCK. In the experiment, the car is set-up to autonomously explore its surroundings. The US I-BLOCK will continuously measure the distance from it to the nearest obstacles and compare with an assigned value, e.g. 5 cm. If the measured range is less than the assigned value, the US I-BLOCKS will send a command to RF transmitting I-BLOCK that will be encoded to send a signal to the RF I-BLOCK receiver in air. The signal will be decoded and transferred via physical connection to the sound generator I-BLOCK. After receiving the signal the sound generator will generate a sound as alarm to inform that the car meet obstacles. Obviously, distance measured input from the environmental surroundings will be invisibly interpreted in to melody on the user's hand in the user's perspective of no existing command-line, GUI, etc. Here, users are playing with a LEGO game as using everyday object.

## 6. DISCUSSION

Functional modules of distributed modular systems allows people to freely utilize newly technological solutions in which devices, that are small, smart, easy to develop and easy to use, are integrated into everyday objects in our surrounding environment. When existing many different research directions to approach technological solutions for ubiquitous robotic applications, we have discovered a new sense of direction inspired from adaptive possibilities of agent in a multi-agent system. In the direction, we have developed distributed modular systems in which each module includes individual functionality of communication capabilities among them and interactive possibilities with environmental surroundings, where each module of the systems will adaptively act as individual agent in agent-systems. Based on investigating advanced aspects of agent-based computing, a wide range of application of distributed modular systems in pervasive robotics such as behavior-based robots, human-robot interaction, cooperative robots, etc has been implemented to demonstrate on the research trends.

In the first scenario, users, children in particular are easy do *"programming by building"* in order to build up a "corridor tracker". Imagine that children without understanding of computer and/or robot play assemble toys with a book of image instruction. Taking two minutes, the robot constructed obtains sufficient characteristics to behave as an edutainment robot. Sill using modules extra increased by other functional modules and LEGO material, a group of robots that can cooperatively behave have been developed. The subject of cooperative autonomous vehicles is always difficult to find a good solution but very interesting to discover new aspects of the evolution. In the second scenario, the global communication has been used to make communicating interaction among robots in which behavior of each robot is possibly depended on other robots' behavior or is employed to control behavior of other robots. We have evolved infrared sensor fusion modules to investigate cooperative behavior of mobile robots by using the concept of local communication that each robot can communicate with others in its vicinity. Each solution abovementioned has more or less advantages and disadvantages: local communication is direct, fast and easy to recognize relative position and orientation among robots but it only effects in its vicinity; global communication can operates in wide area but it is low speed and indirect communication of position between robots. Hence, the best solution for autonomous cooperative robots should be combination of advantages of the technologies. However, it is very interesting thing here that user takes five minutes to assemble a cooperative autonomous vehicles with available smart modules and materials. Continuously, in the direction to explore invisibly interactive relationship between humans and computers/robots, we have just defined a new concept of "invisible human robot interaction, In-HRI". In the scenario, a mobile robot and a remote controller are assembled from functional modules. In the user's perspective, there exist only tangible toys, no computers and no electronic devices. Here, computing devices is completely invisible and disappearing, instead of an interesting game of the mobile robot that is remotely controlled by user, all of them are embedded into everyday objects. This is possible manner, based on the functional modules preprogrammed.

## 7. CONCLUSION & FUTURE WORKS

In this paper, we present the varieties of robotic experiments related to different research fields. In different approaches, adaptive relationship between building blocks is appropriative to adaptive interaction of agents in the multi-agents system. But, all of such experiments have been involved from intelligent building blocks by using *tangible programming language*, so called *"programming by building"*. Based on substantial experiences gained, traditional concepts used I-BLOCKS has been evolved though a variety of application in different research directions in which some of them is beyond their original concepts. Further, we wish to contribute further to the development of new perspective of how to build a ubiquitous heterogeneous robotic applications from distributed modules that have capabilities of self-processing and communication in distributed modular systems.

In the ubiquitous applications, we are emphasizing on research approaches of distributed modular systems which user are easy to create an intelligent system, based on smart device available. However, the modules used for applications abovementioned obtain limitation of mechanical connection, strength of processing and communication. Therefore, we have currently evolved a new prototype of I-BLOCKS which are cubic modules including six physical connection interfaces and a more powerful microprocessor to increase processing power for individual module as well as systems. In the future, we will develop a couple of reconfigurable adaptive modular robots that can possible obtain complex behaviors.

In conclusion, the paper describes a new exploration for ubiquitous robotic applications based on distributed modular systems, which are built up from module including adaptive and interactive possibilities with surrounding environments and communication capabilities among them. Specially, all of the robotic systems as everyday objects in pervasive environments are always *open distributed systems* (ODS), which can easy change morphologies, characteristics and properties because they are almost developed from hardware devices called "*modular artefacts*" [3] and software implementations called *tangible programming language (programming by building)*.

**Acknowledgement**

Part of implementation presented in the paper has been developed by Trung Dung Ngo in his thesis works. We are pleased to acknowledge Jacob Nielsen collaborating in programming. The work is an added part of Danish National Research Council project "Intelligent Artefacts".

**References:**

[1]. Lund.H.H. Intelligent Artefacts. In Sugisaka and Tanaka, editors, *Proceedings of 8th International Symposium on Artificial Life and Robotics*. ISAROB, Oita, 2003.

[2]. Ferber .J. Multi-agent systems: An introduction to distributed artificial intelligence, *Addison Wesley*, 1999.

[3]. Ngo.T.D, Lund.H.H. Modular Artefacts. *Component-Oriented Approaches to Context-aware Computing*, ECOOP'04, Oslo, Norway, June14, 2004

[4]. Weiser.M, The computer for the 21st century, Published in Scientific American, 1991.

[5]. Hazas.M, Ward.A. A high performance privacy-oriented location system. *In processing of the first IEEE International Conference on Pervasive Computing and Communications (PerCom2003), pages 216-223*, Dallas-Fort Worth, USA, March 2003.

[6]. G. Riva, P. Lorenti, M. Lunghi, F. Vatalaro, F. Davide. Presence 2010: *The Emergence of Ambient Intelligence*, *Ios Press*, Amsterdam, The Nertherland, 2003

[7]. A.Schmidt. Implicit Human Computer Interaction Through Context. *Personal Technologies* Volume 4(2&3), June 2000. pp191-199

[8]. C. Plessl, R. Enzler, H.Walder, J.Beutel, M. Plazner. L.Thiele. G Troster. The case of reconfigurable hardware in wearable computing, *Pers Ubiquit Computing*, 2003.

[9]. R.C. Arkin. Behavior-Based Robotics. *MIT Press*. CA, 1998

[10]. Lund.H.H. Neural Building Blocks, *In 1th International IEEE EMB Conference in Neural Engineering*, Capri, Italia, March 20-22. IEEE Press.

[11]. L.E. Navarro-Serment, R. Grabowski, C.J.J. Paredis, P.K. Khosla, Modularity in Small Distributed Robots, n *Proceedings of the SPIE conference on Sensor Fusion and Decentralized Control in Robotic Systems II*, Boston, MA, September 19-22, 1999.