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Reconfigurable Multi Robot Society based on LEGO Mindstorms

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Espoo, 3.8.2009

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Preface

This Master Thesis was developed in 2009 at Helsinki University of Technology to obtain the double degree of Master in Space Science and Technology, given by the Helsinki University of Technology and Luleå University of Technology. The idea to do advanced robots based on LEGO first came after Jürgen Leitner and myself entered a Robotics competition at HRI 2009 [16] and found out that good robotic prototypes could be created with LEGO Mindstorms. When talking to my thesis advisor. Tomi Ylikorpi, the idea about creating a self-reconfigurable multi-robot society, with units made from LEGO Mindstorms arose. I would like to thank Jürgen "Juxi" Leitner for inviting me to that robotics competition that started all of this and also Tomi Ylikorpi for all those ideas and feedback that helped me realize what I had to do and achieve it on time. A lot of thanks also to Steven Canvin from the LEGO Mindstorms Team and Eemeli Aro for supplying the Lego NXT Sets and Professors Aarne Halme and Kalevi Hyyppä for their very important feedback throughout the development of this thesis.

Special thanks to my parents Rodrigo and Barbara, for supporting me all those years in the fulfillment of my studies and my dreams, without that support I would never have tried to take this path that seemed so long and almost impossible at the beginning but that is now a reality for me. And to my wife Marcela, thank you so much for believing in me, for accompanying me in this journey through time and space and all these countries with very cold weather and difficult languages, but most importantly for being there for me giving me strength when mine seemed not to be enough.

Otaniemi, August 3, 2009

David Leal-Martínez

Helsinki University of Technology   Abstract of the Master's Thesis

Author:	David Leal Martínez		
Title of the thesis:	Reconfigurable multi robot society based on Lego mindstorms		
Date:	August 3, 2009	**Number of pages:**	64
Faculty:	Faculty of Electronics, Communications and Automation		
Department:	Automation and Systems Technology		
Program:	Master's Degree Programme in Space Science and Technology		
Professorship:	Automation Technology (Aut-84)		
Supervisors:	Professor Aarne Halme (TKK)		
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Instructor:	Tomi Ylikorpi (TKK)		

Reconfigurable multirobot societies is a young area of robotics that promises versatility, robustness and low cost as is relies on a society of multiple robots that will be able to perform an immeasurable amount of different tasks, tasks that not even were thought of at design time. In order to create a new reconfigurable multi robot society from scratch that could be developed fast and with low costs, it was opted to create a prototype from LEGO Mindstorms NXT equipment, complemented with some expansion electronics developed to expand the capabilities of the existing LEGO Mindstorms NXT system. This work describes the successful creation of a reconfigurable multi robot society based on the LEGO Mindstorms NXT systems, as well as the description of two prototypes that were created on the way and were not successful.

Keywords: mobile robots, reconfigurable, robot society, LEGO Mindstorms

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Symbols and Abbreviations

API	Application programming interface
CMS	Centimeters
I2C	Inter integrated circuit
LED	Light emitting diode
NBC	Next Bytes Codes
NXC	Not Exactly C
PWM	Pulse Width Modulated
TKK	Teknillinen korkeakoulu
TWI	Two wire interface
VI	LabVIEW Virtual Instrument

Foreword

This thesis shows the work of the author and his efforts to create a reconfigurable multirobot society based in the LEGO Mindstorms NXT platform, proving the platform’s capabilities in robotics development, and demonstrating the possibilities to improve its performance by adding extra electronics, all this with the aim to test it as a low-cost implementation for fast robotic prototyping. The work was performed at Automation Technology Laboratory of Helsinki University of Technology, and the society also took part of the Multi-Robot Teaming Challenge of the robotics workshop at the International Joint Conference on Artificial Intelligence on July 2009 in Pasadena, California.

Chapter 1

Introduction

In this new age of robotics, having robots perform simple tasks, is no longer good enough. Recently, there has been a lot of research in trying to make robots more versatile and able to perform more functions. This attempt avoid having an over population of single purpose robots that will not only take much time and money to create and develop, but will also saturate spaces with too many units, thus reducing the overall performance of all units, and even humans, in their vicinity.

This introduction will present the term “Reconfigurable Multirobot Systems”, and will define all of its aspects, next chapter will describe some examples of state of the art systems currently being developed in different research centers across the world. Chapters 3 will describe the Hardware and Software capabilities of the Robotic units created by the author for this thesis work, and Chapter 4 will describe the operating principles of the units when working together as a society. Chapter 5 will describe the previous prototypes of units created by the author at the early stages of the thesis work and the reasons why these prototypes were abandoned. Finally, Chapter 6 will present the conclusions.

Two areas in the branch of robotics that have been growing in the last few years are:

Reconfigurable

This kind of robots can ‘transform’ or change their own structure or coordinate with other robots to re-arrange their position to create a larger structure, so that they can perform multiple functions, sometimes even functions very different from each other, and most importantly functions that were not thought of when the system was designed.

Cooperative

Cooperative Mobile Robotics, are distributed robotics systems, that are characterized by having a group of robots that interact with each other to reach a common goal.

Self-Reconfigurable robotics systems have been, in the last two decades, trying to reach a state where this kind of robotics can have a significant advantage over any other robotic system. By fulfilling the promise of being *Versatile*, *Robust*, and *Low Cost*, this kind of systems would be able to replace any other dedicated robotic system, by reconfiguring and doing the same task, and being able to reconfigure at any time to fulfill any other need that should arise, and all this with the same hardware and software. Also, hardware could be mass produced to reduce the overall cost of the system. An artistic image of such a system operating in space can be seen in Fig1.

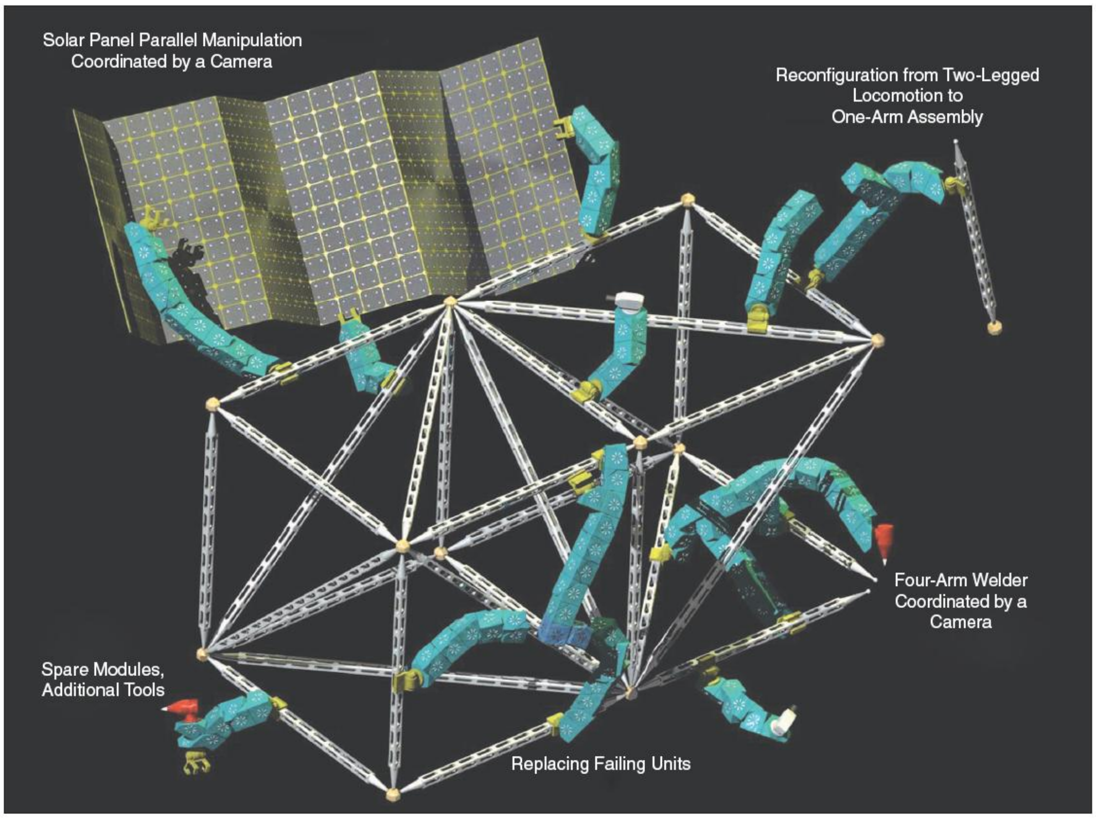
Solar Panel Parallel Manipulation Coordinated by a Camera
Reconfiguration from Two-Legged Locomotion to One-Arm Assembly
Four-Arm Welder Coordinated by a Camera
Spare Modules, Additional Tools
Replacing Failing Units

Fig. 1. Artistic example of a modular robotics group in a space application using a Chain / Tree architecture, modules can be seen performing different tasks, such as welding, replacing faulty units, assembly and more, from [11].

1.1 Multirobot Architectures

Reconfigurable multirobot systems can have many different types of architectures, depending on the goal of each system, and the approach used in order to reach it. Some of the different architectural features that need to be taken into account in order to create or even analyze any multirobot system are described in the following section.

1.1.1 Architectural Groups

Modular, self reconfigurable robotics can be classified into three groups depending on their geometric arrangement of units.

Chain / Tree

The units in this architecture are connected in a string or tree topology, this architecture can fold up to fill a space, but the overall structure is still serial see example in Fig.2 (b). The strength of this architecture is that it can in principle reach any point in a three dimensional space, making it suitable for many tasks, however also increasing the complexity of the software for controlling it.

Lattice

In this schema, units are arranged and connected in a regular three dimensional pattern, for example as a cube or square matrix or any three dimensional geometric pattern. This schema can move several units in parallel, and the control algorithm can be a simple, open loop system as any particular unit may only move to a limited number of neighboring units or places as can be seen in Fig.2 (a). This results in a very scalable solution.

Mobile

This kind of architecture does not have the units physically attached at all times, it’s based on a number of mobile units that can move around large areas to, for example, fuse together their sensor data and be able to cover larger areas. Part of it can hook up and become a Chain or Lattice structure as needed.

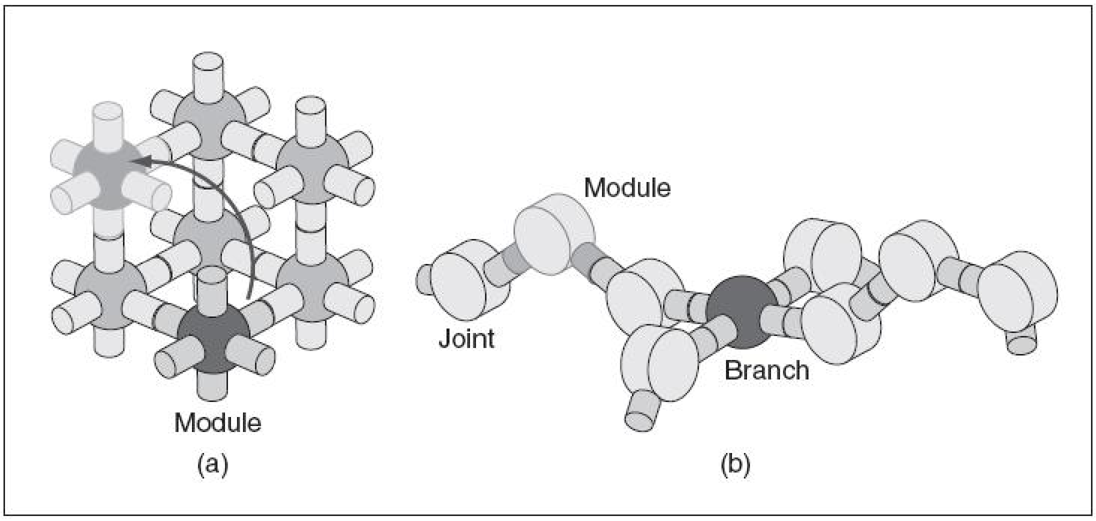

Fig. 2. Types of Architectural groups Lattice (a), Chain/Tree (b), from [9]

1.1.2 Organizational Structure

The organizational structure of the group of robots can be either centralized or decentralized, or a combination of the two, depending of the way the system is to be controlled. It can be:

Centralized

This is a system that will depend entirely on a central unit (either a unit presently among the group or a command center far from the actual position of the group) that will command the entire group to reach the goal.

Decentralized

A system lacking a central controlling agent, each agent has the same level of ‘authority’ inside the group. This kind could be considered more challenging, as each unit must have the computing power to analyze the situation, process the data and take action.

Hybrid

A mixture of both schemas, a clear example being the kind of architecture where there is no central control from the outside, and when a problem or situation requiring the group to take action, a leading unit will arise and coordinate the rest to reach the goal.

1.1.3 Types of Units

The units in the group, both physically and in terms of computing power, can be either Homogeneous or Heterogeneous. This decision will heavily influence the complexity of the way units perceive each other and eventually how their interaction is achieved.

Homogeneous

When all the units are exactly the same, they have the great advantage that every unit knows the dimensions, capabilities and constraints of the rest of the units in the group, and can know what to expect from them, as well as predict the unit’s position and configuration at a given time. This is the most frequently used type of unit when it comes to Modular reconfigurable units.

Heterogeneous

Units in the group could have different capabilities and physical construction. This will increase the complexity of the interaction between units, but also offers the advantage of having specialized units for some tasks.

1.1.4 Principle of operation

The way the units are moved when reconfiguring can be in one of the two following ways:

Deterministic

Units are reconfigured by being directly manipulated to their destination, with a full knowledge of the unit’s position and orientation at all times by either sensing or calculating the position of the unit according to the position and movement over time, as reconfiguration times can be guaranteed. Usually macro systems using either a chain or mobile architecture use this kind of principle of operation.

Stochastic

In this classification type, when a reconfiguration is taking place, the units move using statistical processes (e.g. Brownian motion). There are many paths the unit could take to reach its destination, and there are usually many units that could take a certain position, because of this the location of any unit not connected to the main structure is impossible to know at any given time as is reconfiguration time. This kind of reconfiguration is best for micro scale systems.

Chapter 2

State of the Art Systems

In this Chapter, some state of the art systems from many different kinds of architectures, organizational structures and with different types of principles of operation will be shown. In Table 1 there is a list of self-reconfigurable modular systems that have been developed in the recent years from [11]; showing the class they belong to (chain, lattice, mobile, stochastic or hybrid), the Degrees Of Freedom (DOF, in this column the number of degrees of freedom of the units and weather they move in 2-D or 3D are shown), the author, where (affiliation) and what year they were developed.

Table 1. List of some self-reconfigurable modular systems that exist today.

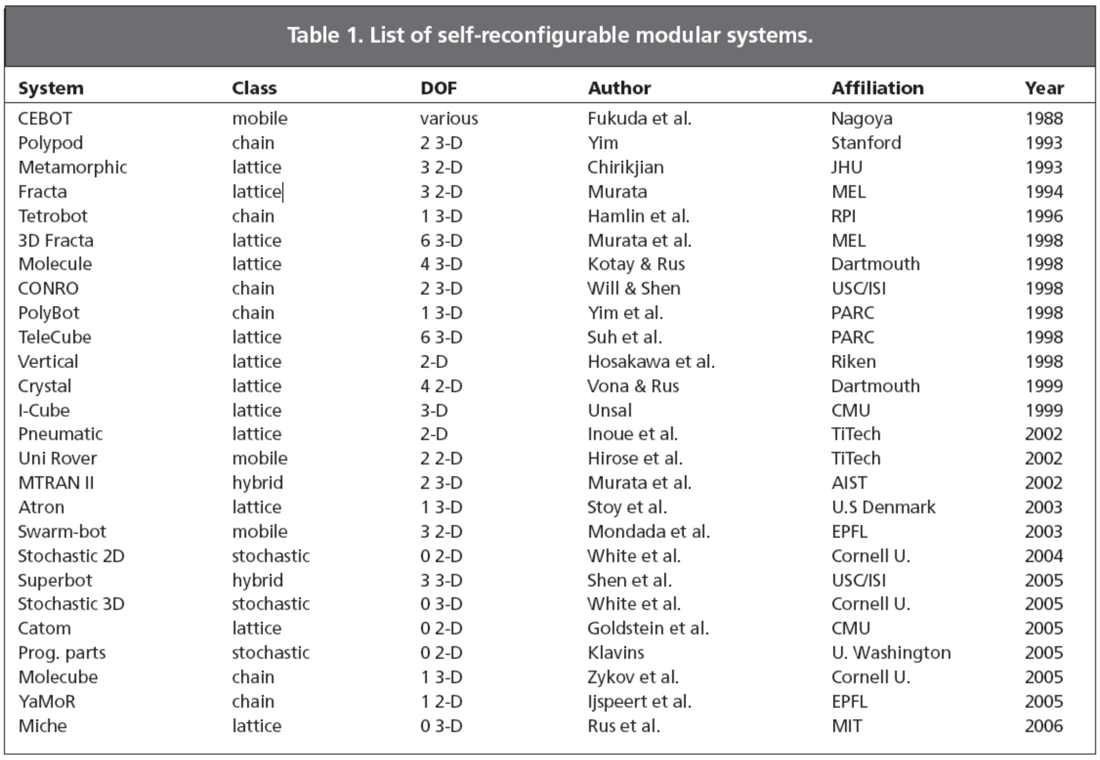

Table 1. List of self-reconfigurable modular systems.

System	Class	DOF	Author	Affiliation	Year
CEBOT	mobile	various	Fukuda et al.	Nagoya	1988
Polypod	chain	2 3-D	Yim	Stanford	1993
Metamorphic	lattice	3 2-D	Chirikjian	JHU	1993
Fracta	lattice	3 2-D	Murata	MEL	1994
Tetrobot	chain	1 3-D	Hamlin et al.	RPI	1996
3D Fracta	lattice	6 3-D	Murata et al.	MEL	1998
Molecule	lattice	4 3-D	Kotay & Rus	Dartmouth	1998
CONRO	chain	2 3-D	Will & Shen	USC/ISI	1998
PolyBot	chain	1 3-D	Yim et al.	PARC	1998
TeleCube	lattice	6 3-D	Suh et al.	PARC	1998
Vertical	lattice	2-D	Hosakawa et al.	Riken	1998
Crystal	lattice	4 2-D	Vona & Rus	Dartmouth	1999
I-Cube	lattice	3-D	Unsal	CMU	1999
Pneumatic	lattice	2-D	Inoue et al.	TiTech	2002
Uni Rover	mobile	2 2-D	Hirose et al.	TiTech	2002
MTRAN II	hybrid	2 3-D	Murata et al.	AIST	2002
Atron	lattice	1 3-D	Stoy et al.	U.S Denmark	2003
Swarm-bot	mobile	3 2-D	Mondada et al.	EPFL	2003
Stochastic 2D	stochastic	0 2-D	White et al.	Cornell U.	2004
Superbot	hybrid	3 3-D	Shen et al.	USC/ISI	2005
Stochastic 3D	stochastic	0 3-D	White et al.	Cornell U.	2005
Catom	lattice	0 2-D	Goldstein et al.	CMU	2005
Prog. parts	stochastic	0 2-D	Klavins	U. Washington	2005
Molecube	chain	1 3-D	Zykov et al.	Cornell U.	2005
YaMoR	chain	1 2-D	Ijspeert et al.	EPFL	2005
Miche	lattice	0 3-D	Rus et al.	MIT	2006

The systems described in the following sections are not the only systems or the most representative ones, these are just the ones chosen by the author to give the reader an impression of the kinds of systems that exist. For more information regarding this and some more systems the reader could go to [11, 12, and 13].

2.1 Stochastic 3D (2005)

This system is an implementation of a self assembly and self-reconfiguration, stochastic, homogeneous system in which no unit has any sort of locomotion; the units rely on Brownian motions induced by the agitation of the surrounding medium. These units also lack of any sort of inner energy supply, so they can draw power from the growing system only when they are attached to it as described on [1].

As any system grows in number of units, it is very difficult and resource consuming to keep track of every unit at any given time, so in order to be able to break the current boundaries of size and number or units in a system, this stochastic method was implemented in a simulation environment and later on two different physical three-dimensional stochastic modular robot systems that self-reconfigure in fluids.

The later of the two implementations was based on having small robotic cubes submerged into a liquid and having a pump drawing the liquid out and putting the liquid back in through some other inlets. This to create a flow in the fluid that would make the units be drawn to it.

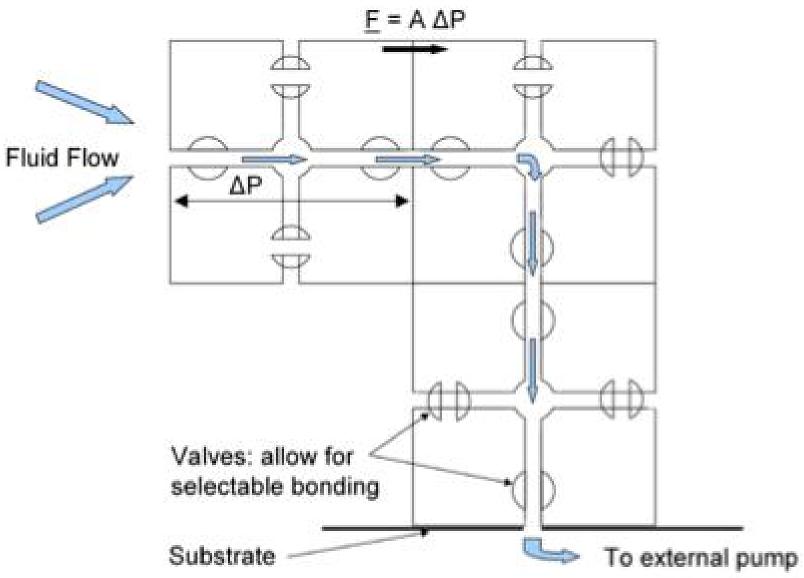

Fig. 3. A 2D representation of the principle of operation of the stochastic system

Each individual unit consists of a cube, with a hermaphroditic (it has no defined genre) electrical connector, for power and control, and a set of valves that would be opened and closed in order to attract the next unit to a certain given position as in Figure 4 below.

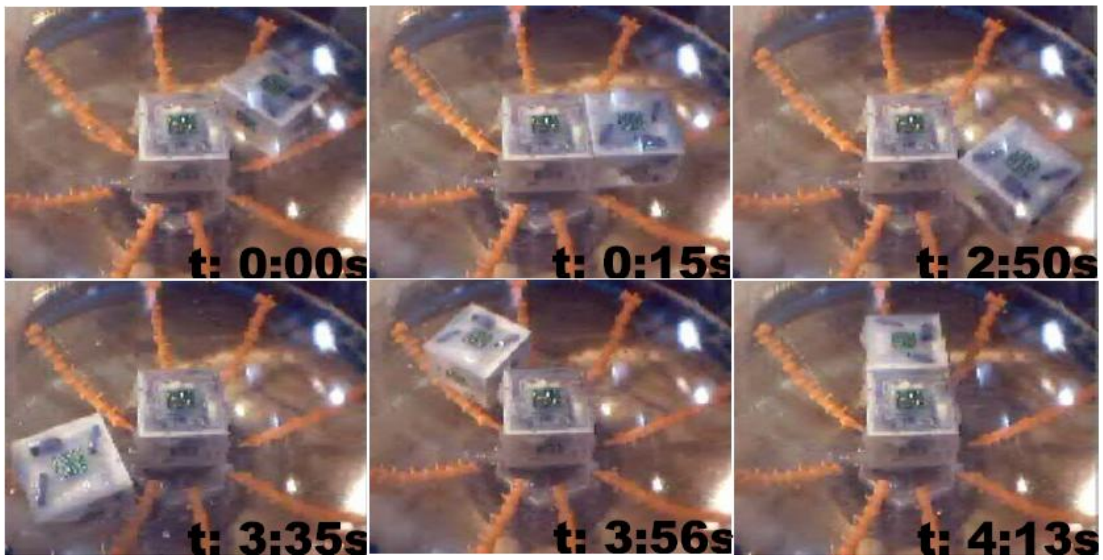

Fig. 4. Experiment III of [1], depicting the mode of operation of this system from being attached to the right side of the central cube at t 15 seconds, to reattaching to the upper side or it almost 4 minutes later.

In Fig 4, an experiment is done to explain the way of operation. First a units is floating free, and when successfully docking in a certain position (at t=15s), the system is reconfigured by closing the valve that kept the cube there, and opening a new one, this way releasing the cube to float free again and move in the substrate until the flow forces it to attach again to the main unit after almost 4 minutes.

2.2 M-Tran III (2005)

M-Tran, short for Modular Transformer, is a lattice–chain hybrid, homogeneous, distributed self-reconfigurable system that has been under development since 1998 by AIST and Tokyo-Tech [5].

This system is formed by small modules composed of two blocks, each half cylindrical and half cubic with 3 possible connection surfaces (see Fig 5 for details)

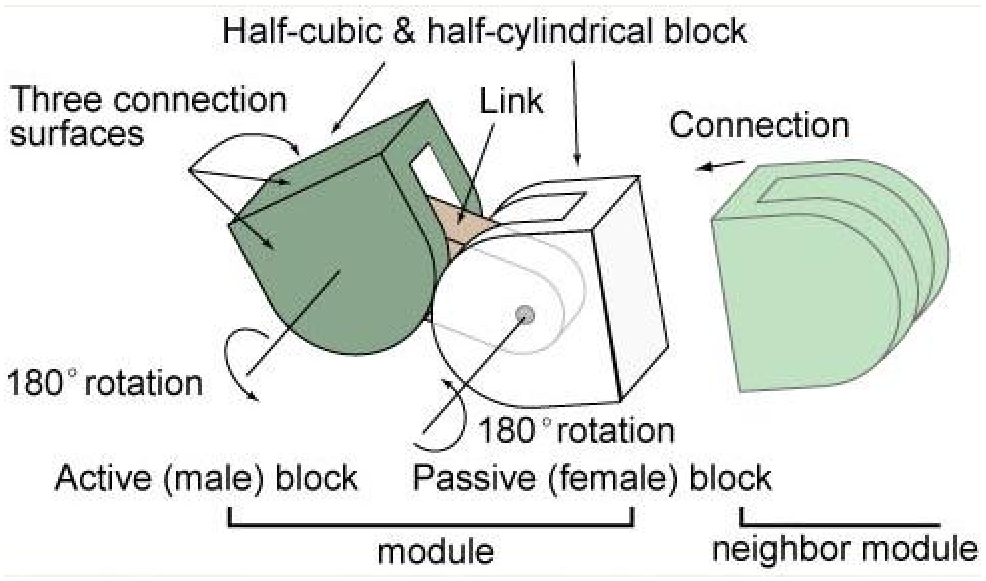

Fig. 5. The M-Tran module with the full description of its connectors.

Each module has a particular gender. On one side, the male controls the connection and is able to couple with any female side of another module, where the female part is passive. Every unit has its own processing unit, and is intelligent enough to work with the modules around it, which makes this a completely distributed autonomous system.

M-Tran tries to use the best of the Lattice and Chain architectures in order to reach a system with a high level of adaptation, which is able to morph into different structures and to move in many different patterns, such as a four legged walker, a snake and a wheel (see Fig 6).

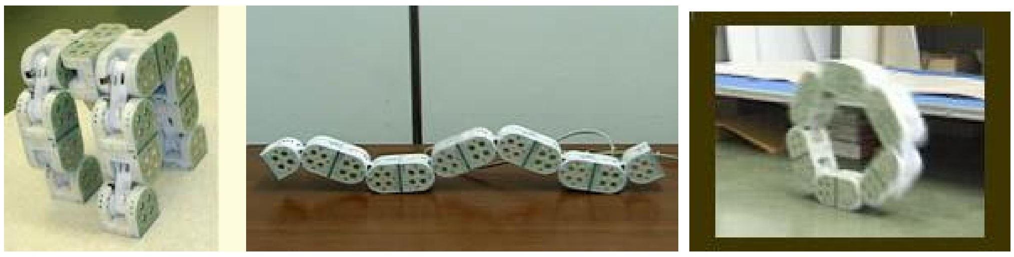

Fig. 6. Different kinds of motion that can be achieved by the M-Tran system: four legged (a) walker; (b) snake; (c) wheel.

2.3 Molecubes (2004 - 2008)

Molecubes is an Open Source, chain structured non homogeneous centralized system built in the Cornell Computational Synthesis Lab, in 2004 [6]. This system aims, among other goals, to prove self-reproduction and offers the promise of modular robotics: to be a *Versatile*, *Robus*t and *Low Cost* way to have a system that can replace specialized machines with fixed bodies and functionalities.

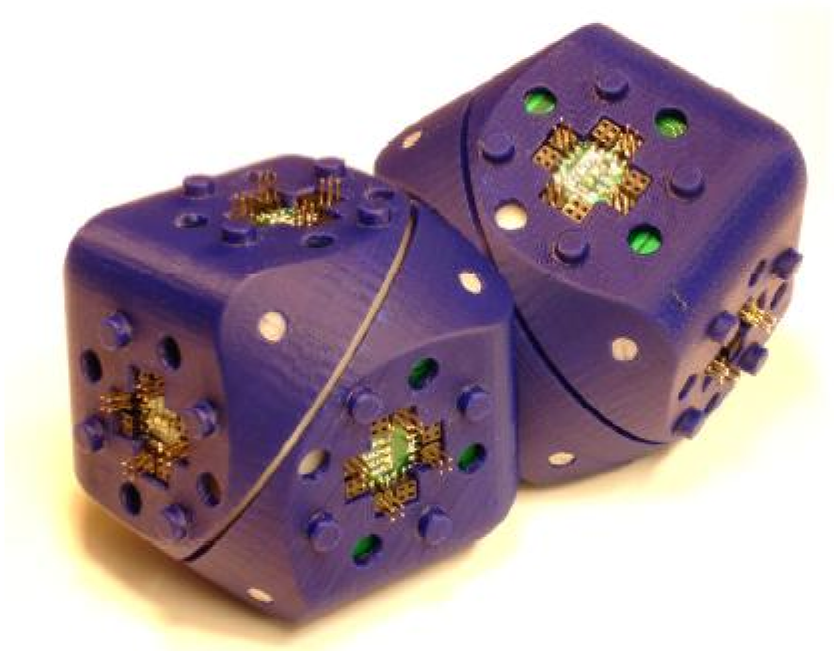

Fig. 7. Example of two Molecubes joined together

Molecubes are cube shaped units that have one degree of freedom across the cube’s longest diagonal (see Fig 7). This system has many kinds of possible units that can interact with each other, and in order to work, any assembled system will require at least one controller unit and one battery module, and as many *Molecubes* and extra modules (actuator modules or even passive modules) as needed to implement the desired structure.

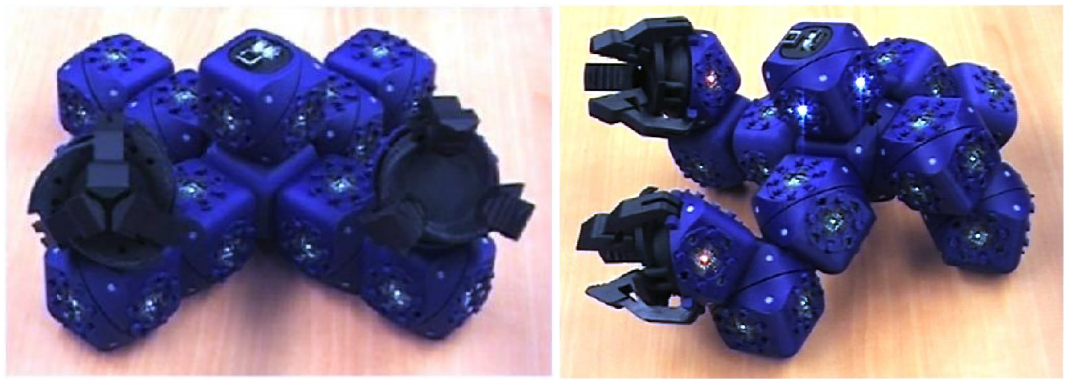

Fig. 8. An assembled Molecubes system in its initial state (left), and the same configuration moving about (right).

In the first version of *Molecubes*, robotic self replication was demonstrated as shown in Fig 9.

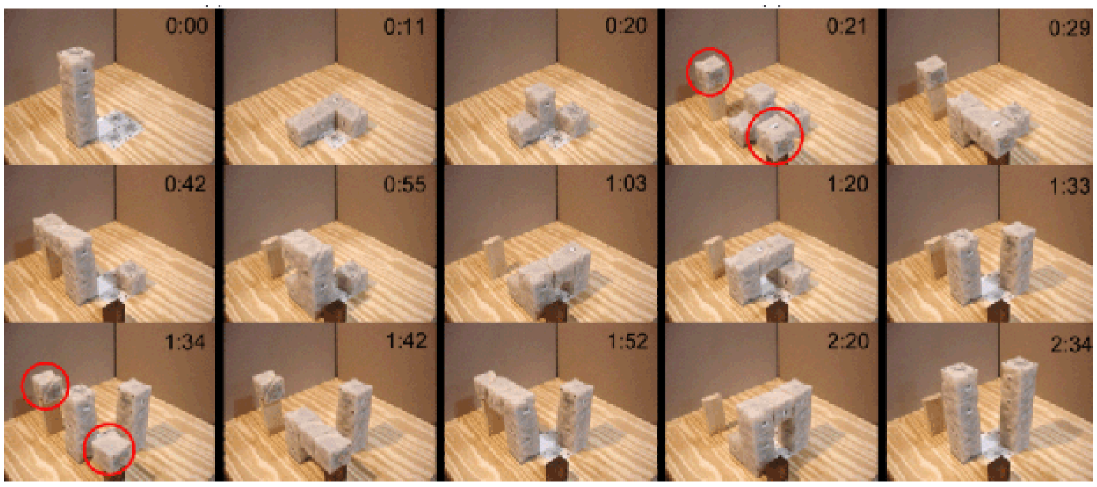

Fig. 9. The earliest version of Molecubes in a self-replication run, where at the start(0:00) there is one unit standing alone, and through the process it will take more cubes and build a unit exactly like it.

This Open Source project provides all the hardware and software details so any person can use their accumulated knowledge in this area and help boost its development for more information please refer to [2,3].

2.4 Swarm Bots (2001-2005) – Swarmanoid (2006-2010)

Swarm Bots is a project is a homogeneous, decentralized system developed by the Information Society Technologies framework programme of the European Commission. The main objective of this project was to “study a novel approach to the design and implementation of self-organizing and self assembling-artifacts” [8].

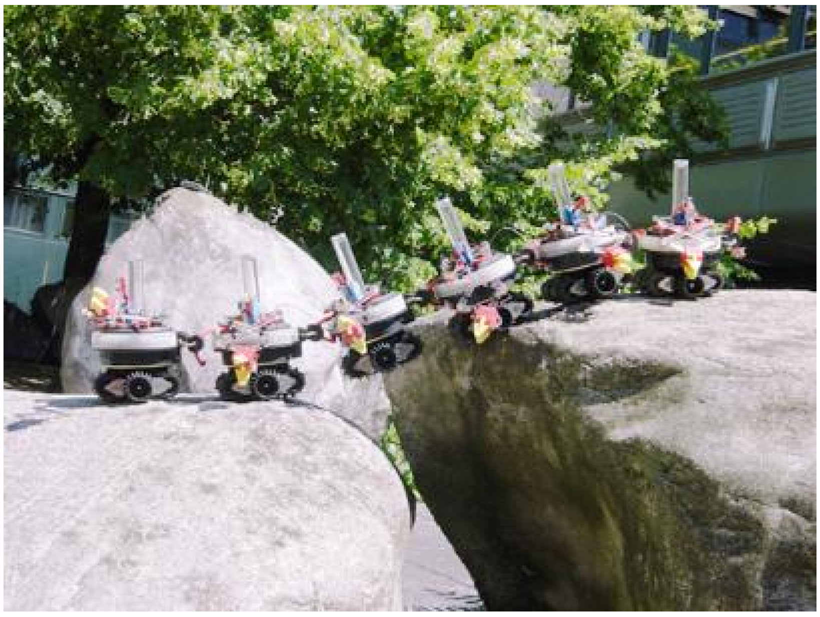

Fig. 10. Swarm-Bot going over a big gap.

Swarm robotics are inspired on the societies of insects, the way these societies are very decentralized and have limited communication abilities among them, and they rely on the use of local information, and emergent behaviors. In this particular implementation a basic single unit is called “S-Bot”, while a group of units joined together for a “Swarm-Bot” such as the one depicted in Fig 10. Each S-Bot is totally autonomous unit (see Fig. 11 for a picture of a S-Bot prototype) and is comprised by the following features:

- 116mm diameter size x 100 mm height.
- All terrain Treels (tracks and wheels) mobility system.
- One degree of freedom rigid arm with gripper
- Three degrees of freedom arm with gripper.
- IR proximity sensors
- Color LEDs around the body
- Light sensors around the body
- Force and torque sensors in the wheels
- 3 axis accelerometers
- Humidity sensors

- Temperature sensors
- Speaker and microphones
- Omni directional camera

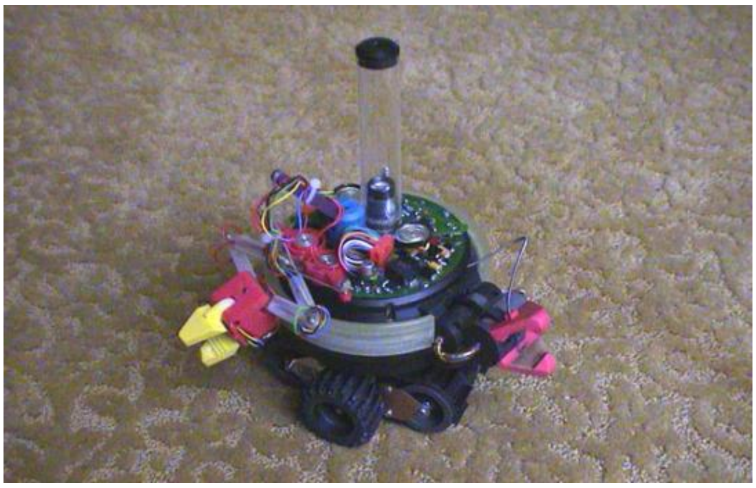

Fig. 11. Single S-Bot unit prototype.

The basic behavioral capabilities that were achieved by the swarm at the time the project ended were:

- Co-ordinated motion
- Hole/obstacle avoidance
- Passing over a hole
- Moving on rough terrain
- Aggregation
- Self assembly
- Functional Self-Assembly
- Adaptive division of labour
- Finding object / goal
- Cooperative transport

This project ended in 2005 and has been succeeded by the Swarmanoid project [14], that is built on the results of the Swarm-Bots project, and now aims at creating a heterogeneous distributed robotic system comprised of heterogeneous robots that could be one of the three unit types: “Foot-bots”, “Hand-bots” or “Eye-bots” and a group of more than two units would comprise a “Swarmanoid”, see Fig 12 for some pictures of the three kinds of units.

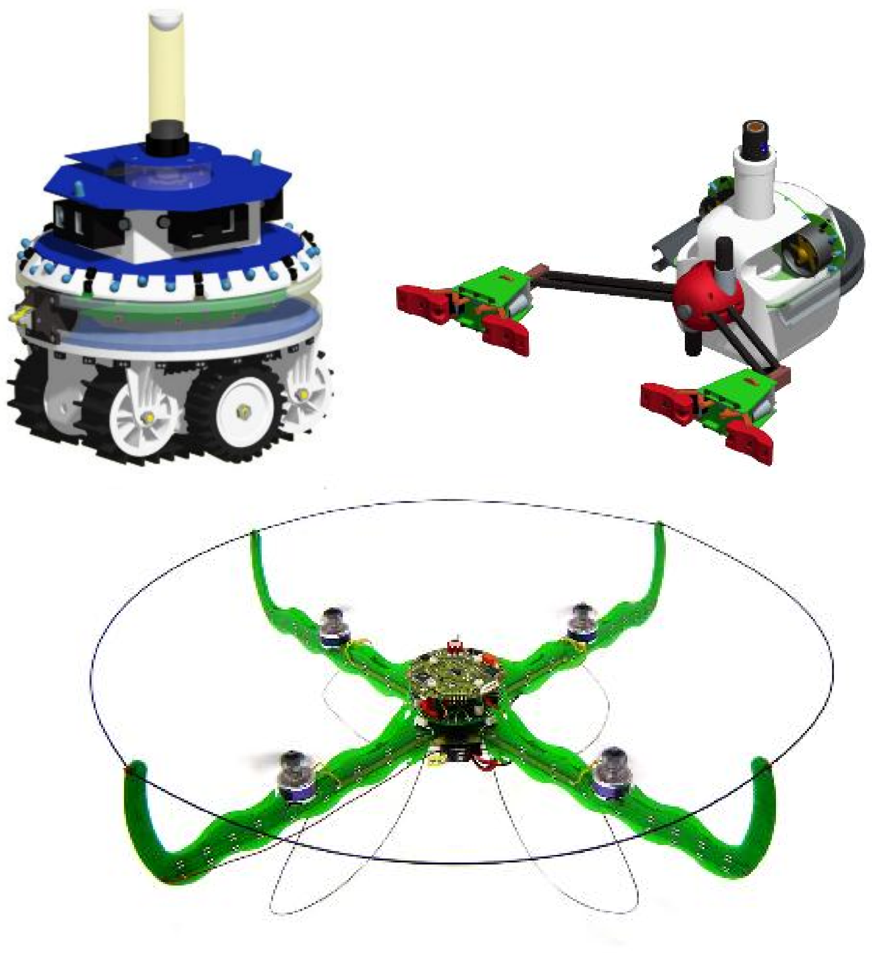

Fig. 12. A Foot-bot (Upper Left), a Hand-bot (Upper Right) and an Eye-bot (Lower Center), the three basic units that could comprise a Swarmanoid.

The Swarmanoid project puts forward an innovative way to build robots that can interact and work inside man-made environments and it is the first to “study how to design, realize and control a heterogeneous swarm robotic system capable of operating in a fully 3-dimensional environment” [14].

Chapter 3

STORM Unit: Hardware and Software description

The Single Traction Octagonal Reconfigurable Machine (STORM) Units are the robotic units that were created by the author to form the society described in Chapter 4, which was designed and built to become a Homogeneous, chain/tree society of Mobile units that would move in the horizontal plane, this is, the units will drive around in the floor and reconfigure themselves by driving around each other and linking to create different shapes that, looked at from above will seem change in 2-D.

In this chapter all their hardware, including sensors structure and connections, will be described, as well as their software capabilities and motion technique.

3.1 Hardware

The units in the system are mostly comprised of LEGO Mindstorms NXT technology, including the main controller unit, sensors, actuators and a set of LEGO pieces that are used to create the mechanical structures. An expansion board was also developed to add some external electronics and expand the capabilities on the LEGO NXT system. All of these components will be described in the following subsections.

3.1.1 NXT Module

The NXT Module is the main controlling unit of the system; it has 4 input ports to acquire data from sensors, and 3 output ports to be used for controlling the actuators, as well as a USB port and Bluetooth wireless connectivity see Fig 13 for a digital representation of this unit. Inside it there are two micro controllers:

- Main Processor: 32 bit ARM processor AT91SAM7S256 that controls the USB and Bluetooth Connectivity, the LCD display, sound system and also controls the CO-Processor unit.
- Co-processor: 8 Bit AVR processor ATMEGA48 that controls the input and output ports, as well as the buttons on top of the unit.

Fig. 13. NXT Module

The NXT module uses an I^2C Bus to communicate through all the input and output ports to reach the actuators and sensors, and SPI to handle the Display and Bluetooth communication.

3.1.2 NXT Sensors

There are 3 main sensors that the units use to get data from the outside world and process it to be able to carry out their functions:

- Touch Sensor: to detect that the gripper has grasped an object, it works a pushbutton and its output is Boolean value ON-OFF.
- Light Sensor: to measure the presence of light and distinguish colors of objects, based on the sfh309-4 Silicon NPN Phototransistor that has a viewing angle of +-12^o.See appendix for more details.
- Ultrasonic Sensor: to measure the distance from the unit to the next object in its line of sight, it can measure up to 2.5 meters with a precision of up + / - 3 cm, and its field of view is 40 degrees per side. See appendix for more details.

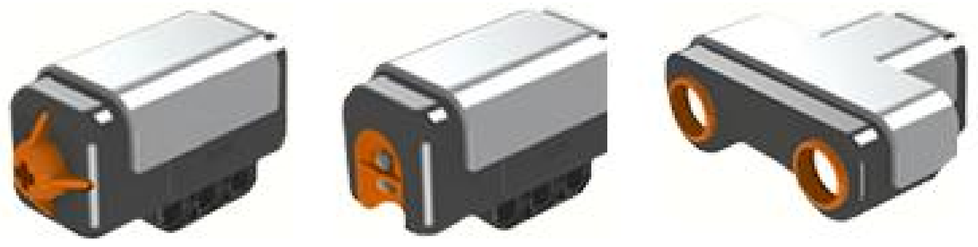

Fig. 14. From left to right touch, light and ultrasonic NXT sensors.

3.1.3 NXT Actuators

Each unit uses three NXT Actuators that can rotate continuously as a DC motor and also have an built-in rotation sensor that can measure both the angle and the amount of rotations the actuator has performed in a certain direction see Fig 15 for an image depicting one of these actuators.

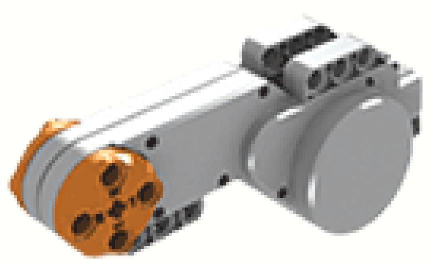

Fig. 15. The NXT actuator.

3.1.4 Expansion Board

As the NXT Brick can only connect to up to 3 actuators through its output ports and up to 4 sensors in the input ports, to expand these constraints, an Expansion board was developed using the ATMega164P micro controller, which is has an I^2C bus to be able to connect to the NXT, as well as 32 programmable I/O lines, Real time clock, Six PWM lines, two serial UARTS, analog comparators, and many other features that make it suitable to expand the current capabilities of the NXT. In Fig 17 there is a picture of an expansion board showing the ATMega164P microcontroller in the middle.

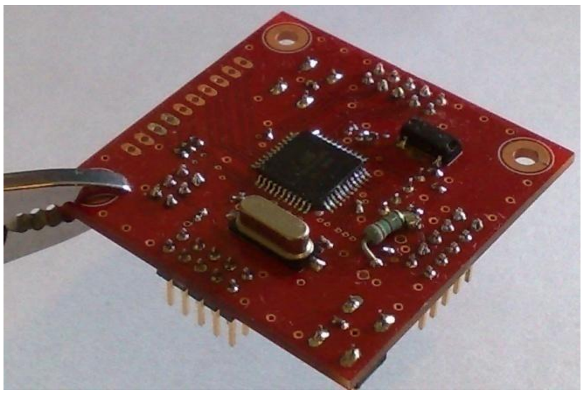
Fig. 16. Expansion Board with the ATMega 164P.

This MCU board was first created by Antti Karjalainen, to use it for interfacing with Zigbee wireless radios [4]. With a few modifications to original design it was adapted to be able to communicate with the NXT via the I^2C port of the microcontroller by adding pull-up resistors to the SDA and SCL lines and removing unnecessary headers.

The expansion board is currently used to add the following functionality to the units:

- Control a servomotor to drive the gripper that will enable the units to attach and detach themselves from one another, see 3.1.5 for details and connections.
- Drive 7 LEDs that will be used to make a certain unit make itself noticeable to a second unit and point the exact place where it wants this unit to approach and attach itself to, see 3.1.6 for details on the LEDs characteristics and electrical connections. For more details about the approach and attach sequences please read section 4.4.1.

3.1.5 NXT – Expansion Board connection

The NXT module uses the I^2C communication protocol to connect and exchange data with the sensors and actuators, so this type of connection was chosen to be able to communicate with the expansion board in a simple and very compatible way, such that it would be connected to the NXT module as if it was another sensor.

As I^2C was invented by Philips and as such is a proprietary protocol, the Expansion board will be using then TWI (two wire interface) to connect to the NXT. TWI is 100% compatible with I^2C but just cannot be called that way because of copyright issues for more details about the communication protocol, way or operation and software examples please refer to Appendix A.

The physical connector that the NXT module uses to connect to and from the sensors and actuators is a special cable manufactures specially for LEGO. This is a six conductors on six positions cable with a plug that is a variant of the RJ-12 standard plug, with the difference that the cable lock on the right side of the connector(see Fig 17), which makes any RJ-12 connector or plug incompatible. For this reason the board was not implemented with a hardware connector plug, and instead the cables were cut on one end and crimped into another kind of connector that could connect to a regular header as shown in Fig 18.

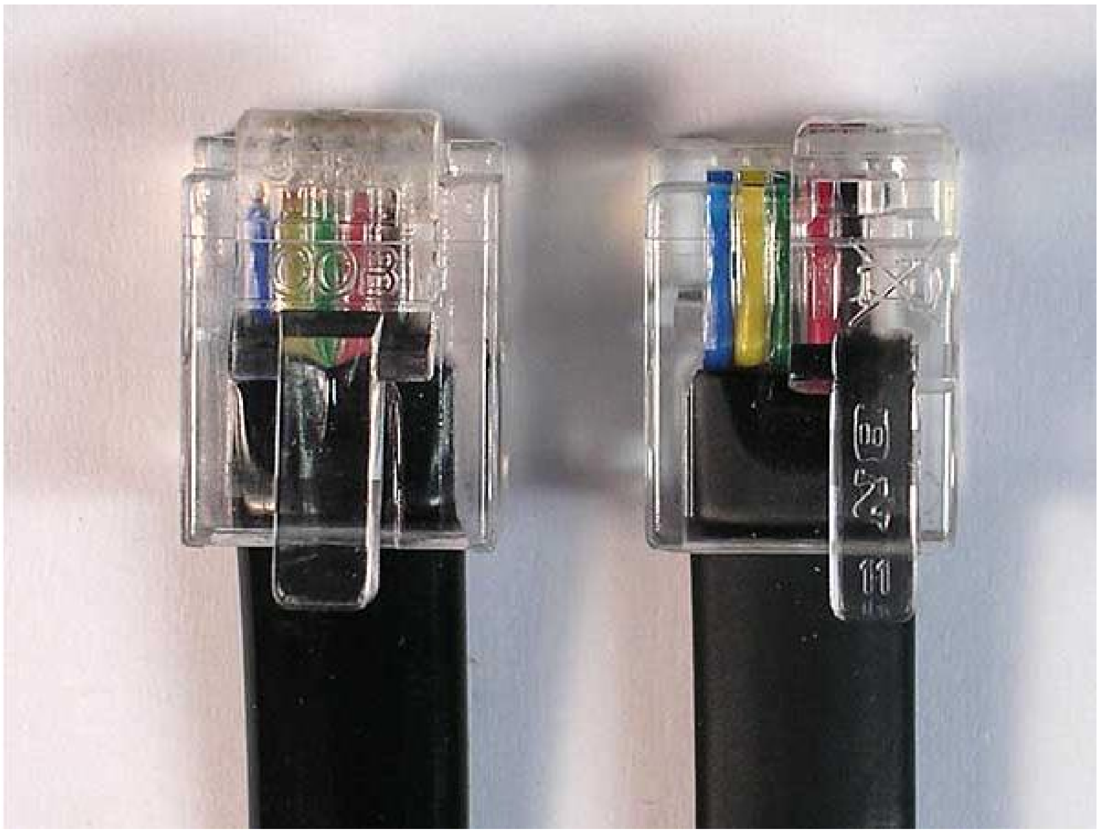

Fig. 17. Expansion Board with the ATMega 164P.

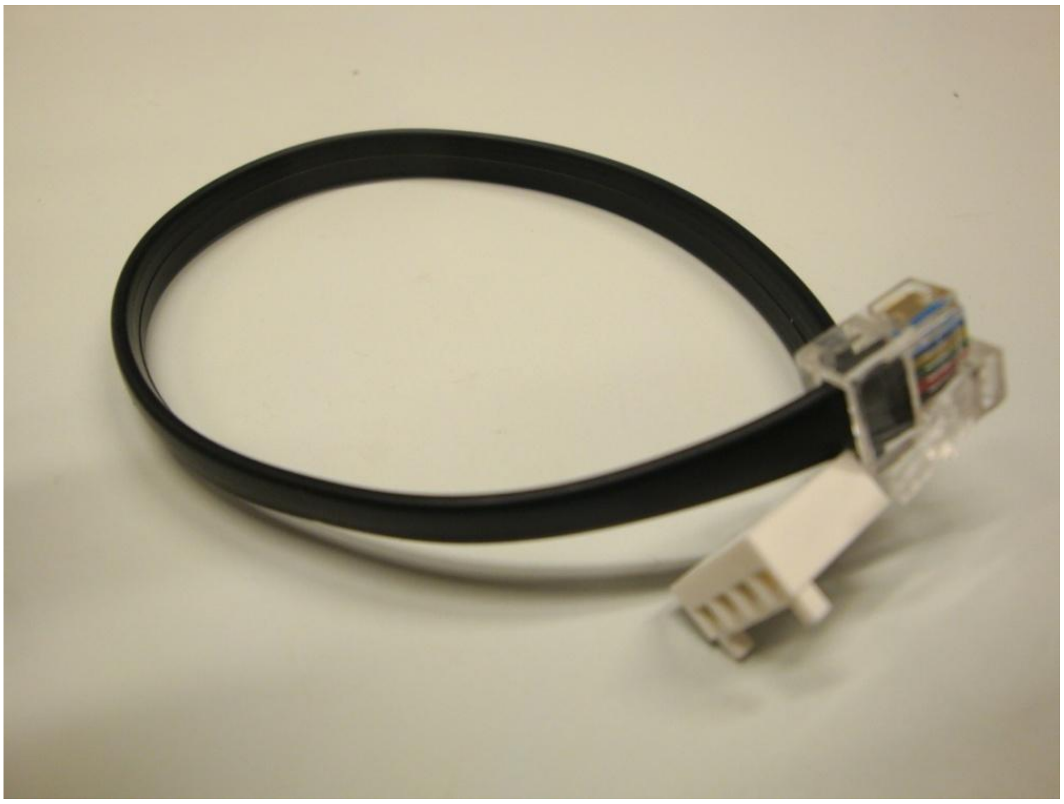

Fig. 18. NXT Module – Expansion board cable adapted to fit a regular header connector.

The connector plug consist of a three wire female header connector (or four depending on the version as one unit got a four pin header for testing and expandability) that connects the blue, yellow and red cables of the original NXT cables into the SDA, SCL and GND pins of the expansion board. SDA and SCL (yellow and blue) connect directly to the “PWR” header pins 1 and 2 while the GND (red) has a wire that goes from the female header of the cable connector to the male header connector on pin 5 of the same header as shown on Fig 19.

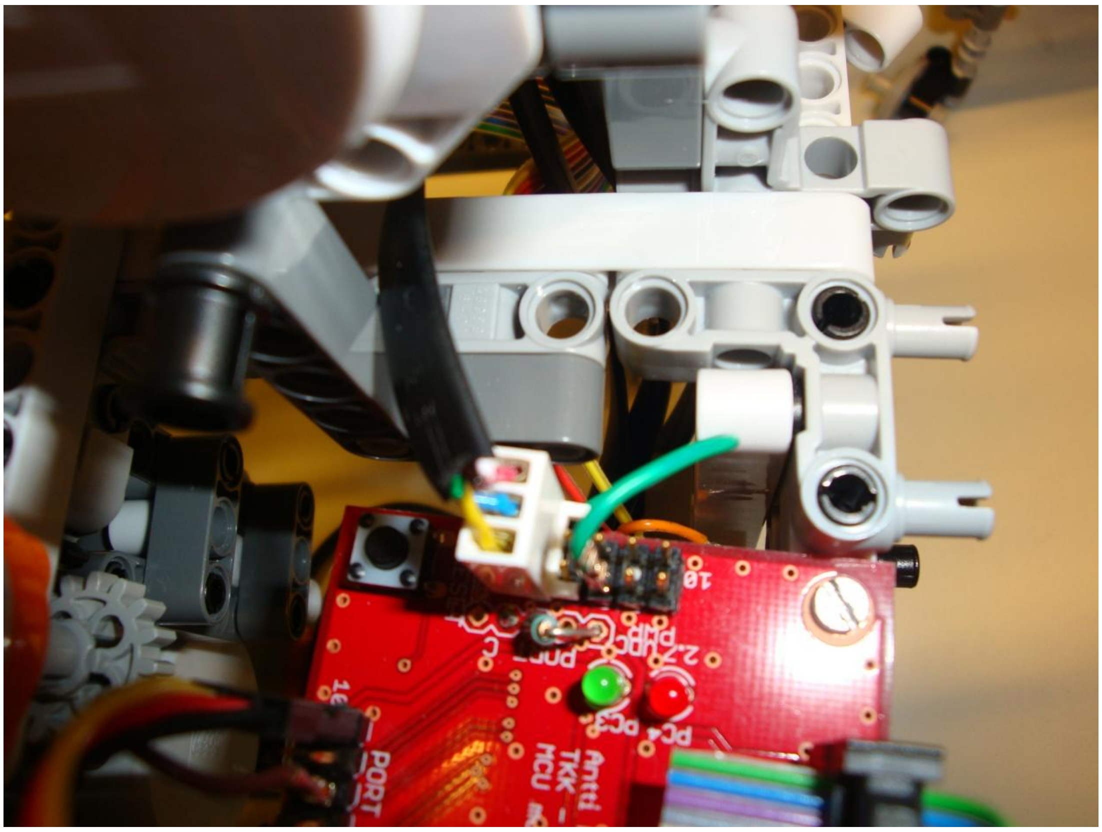

Fig. 19. NXT Module – Expansion board cable adapted to fit a regular header connector.

3.1.6 HiTec HS-422 servo

The HiTec HS-422 servo is a dual oilite bearing, indirect drive servo motor that operates at speed of 0,21sec/60^{o}, and provides 3.3kg.cm at 4.8 V which is the average voltage that feed both the expansion board and the servo. It weights only 45.5g and has a size of 40 x 20 x 36 mm. All these characteristics make it a very good option for using this unit as the one driving the gripper of the units.

3.1.7 Servomotor – Expansion Board connection

The servomotor has a cable coming out that has three wires (VCC, GND and SIGNAL in a female header connector) and is controlled by sending a Pulse Width Modulated (PWM) signal with the desired position to the SIGNAL wire.

To connect it to the Expansion Board, the three pin female header connector must be connected, the black (GND) wire to pin 9 of header “PORT D”, the red (VCC) wire to pin 10 of the same header, and the yellow (SIGNAL) cable has a cable connecting it to the male connector on pin 5 of again header “PORT D”, similar to the NXT cable connection, see Fig 20 for details.

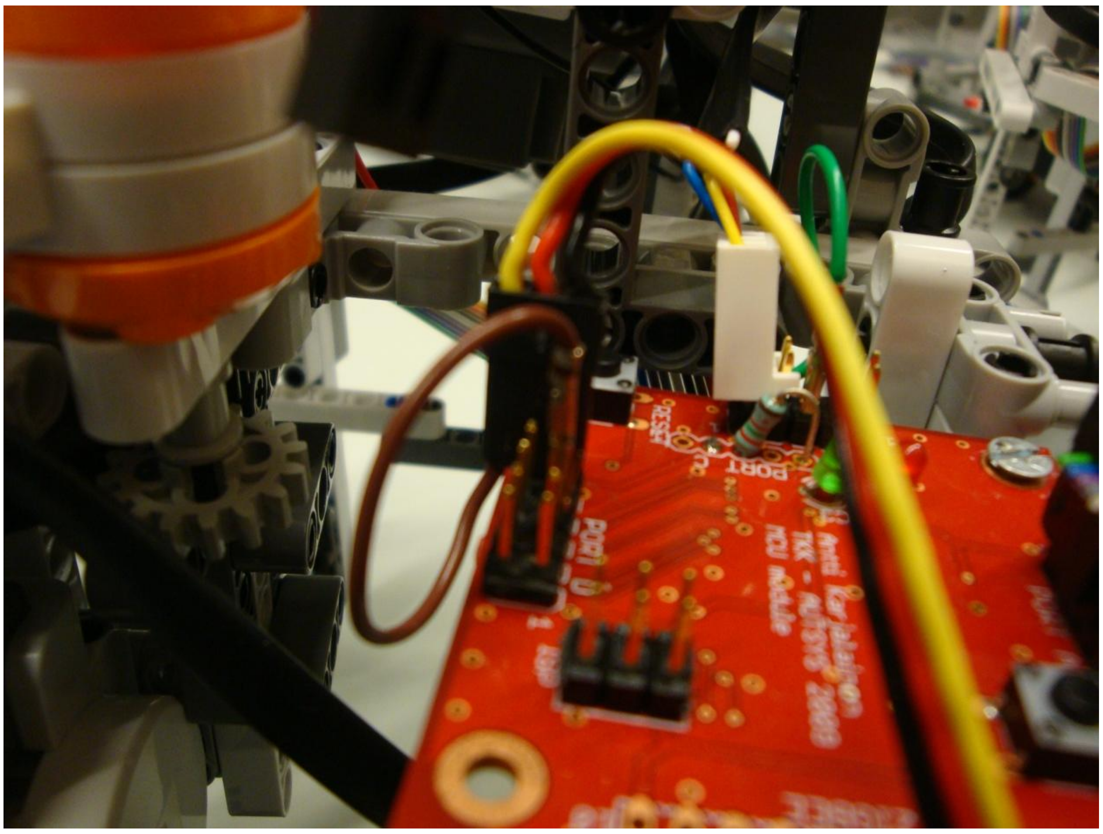

Fig. 20. Servo’s three wire cable connected to the expansion board.

3.1.8 PWM

A PWM is an efficient way of providing different amount of power to an electronic device by switching power ON and OFF at certain intervals. In this particular application, the servomotor is expecting a repeating square wave signal with a period of 20 milliseconds and a varying duty cycle of 1 to 2 milliseconds, this is, a signal that repeats itself every 20 milliseconds and that is pulled high (VCC) for 1 to 2 milliseconds every cycle. The difference in this amount of time the signal is high will be interpreted by the motor as the position the shaft is required to have. A practical example using the particular servo that it's been used in the robot society for the gripper is that if we send a repeating square signal with 1 millisecond duty cycle to the motor, it will position the shaft at 90^{o} from the center position, and when the duty signal is changed to 2 milliseconds the motor will rotate the shaft to be at -90^{o} from the central position, this way opening or closing the gripper in our case.

3.1.9 Light Emitting Diodes

LEDs are connected to seven of the eight facets of the units, and are used to guide another unit to connect in this particular facet. These LED's are attached to the LEGO structure and all connected together with a ribbon cable through a 220 ohm series resistor to the power line (VCC) and to their designated pin in header number *PORT A* of the microcontroller, see Fig 21 to see the way the ribbon cable is connected to *PORT A* and also how an LED is connected to the ribbon cable.

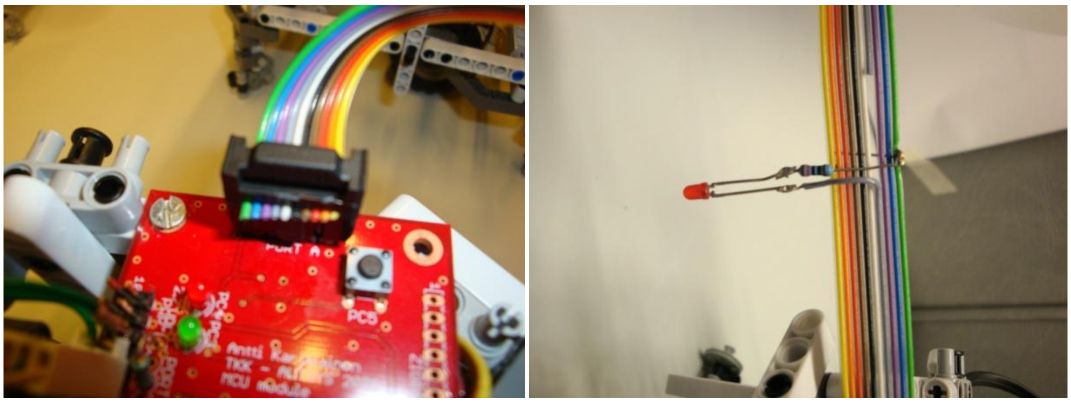

Fig. 21. Ribbon cable connected to *PORT A* header of the expansion board (left) and an LED connected to the ribbon cable (right).

These standard red LED lamps are 2 mm in diameter and have a viewing angle of $50^{o}$and and Intensity 20 mcd. In Fig 22 the position of the LED's on the structure can be appreciated.

3.1.10 Unit – Unit Connection

To communicate with another units, the NXT module has an embedded Bluetooth communication radio, that can create a serial wireless connection between it and any unit within a 10 meters distance in an “inside environment”)

The NXT module is prepared to be connected to 3 other NXT units simultaneously, where one has to be the master of the 3 remaining units, in this mode the units send messages that arrive at the destination unit’s mailbox as plain text messages. Besides that, the module can also connect to another unit via a remote link and order the unit to stop running the current program, run any other particular program, and monitor the status of the incoming and outgoing data of the slave unit.

3.2 Software to Use

3.2.1 NXT Module

The NXT module has its own software “Mindstorms NTX”, which is a programming suite based on Lab View, that provides basic functions to work with simple robots, but is very limited when dealing with multiple units, behaviors and complex structures. Besides this programming software, the NXT module can be programmed in 3 main programming languages as described below.

- NXC: The Not eXactly C (NXC) high level language is similar to C and is based on the low level Next Bytes Codes (NBC) that has an assembly language syntax. The API is very close to C language and there is a good documentation on the syntax and there are some examples for testing all the functions. The NXC programs can be run in the Original firmware of the NXT.
- leJOS: leJOS is a small java virtual machine that was ported in 2006 to work with the NXT module. The API is extremely well documented and examples are provided in the documentation. To be able to work with leJOS, the NXJ firmware has to be downloaded into the NXT module.

- LabVIEW: National Instruments provides the “LabVIEW Toolkit for LEGO Mindstorms NXT”, that has all the necessary tools for making advanced programs in LabVIEW and can run the programs also in the original NXT Firmware.

All the languages were downloaded and tested in order to choose the best one for the application at hand. As NXC did not have much documentation about the I2C communication implementation and the Bluetooth connection was also very basic and complex to implement on a multi unit environment, it was decided not to use it for the system implementation.

After some further testing and implementation of I2C and Bluetooth examples, LabVIEW was chosen to be the programming language because it has available all the LabVIEW tools that includes measuring units and reporting tools that will provide an easier on-target debugging and also a graphical way of representing the code to better illustrate the algorithms to the reader in the following chapters.

3.2.2 AT Mega 164P

The ATMega164P can be programmed in two languages, Assembler and C, with basically the same functionality, therefore, C was chosen for being simpler to implement, and because of the existing subroutines and application notes that are available be adapted to use the I2C to connect to NXT, and PWM to manage servo motors.

3.3 Structure / Architecture

The structure of the units as seen from above resembles that of an octagon with its eight facets as shown in Fig. 22. The body of the robot consists of two main body parts referred to as the “Inner Structure or Motion Subsystem” and the “Outer Structure”. These two parts of the unit are uncoupled and can be rotated totally independent from each other. This will provide the units with direction of traction independent from the structure orientation which is necessary for the units to be able to attach to each other and still be able to orient the motion system to serve the newly formed unit. Both subsystems will be described in the following subsections 3.3.1 and 3.3.2.

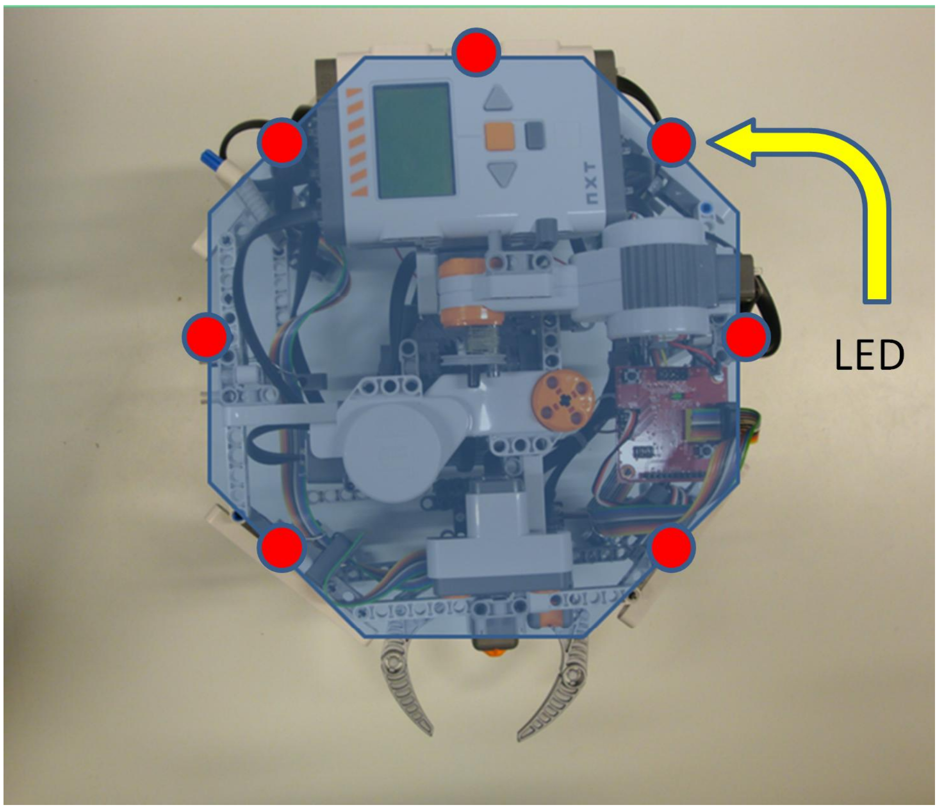

Fig. 22. Unit as seen from above to appreciate its octagonal shape and the position of the LED's, marked by the seven circular dots.

3.3.1 Inner Structure (or Motion Subsystem)

The inner structure is the one that provides the unit with the ability to have traction and move with respect to the floor. This structure is made of a single traction LEGO NXT actuator that is held in place by two spring pistons that are connected to the *primary rotation cog* system that together with the tether attachment will be used for steering / driving purposes and will be explained in section 3.4., see Fig 23 for a picture detailing this subsystem.

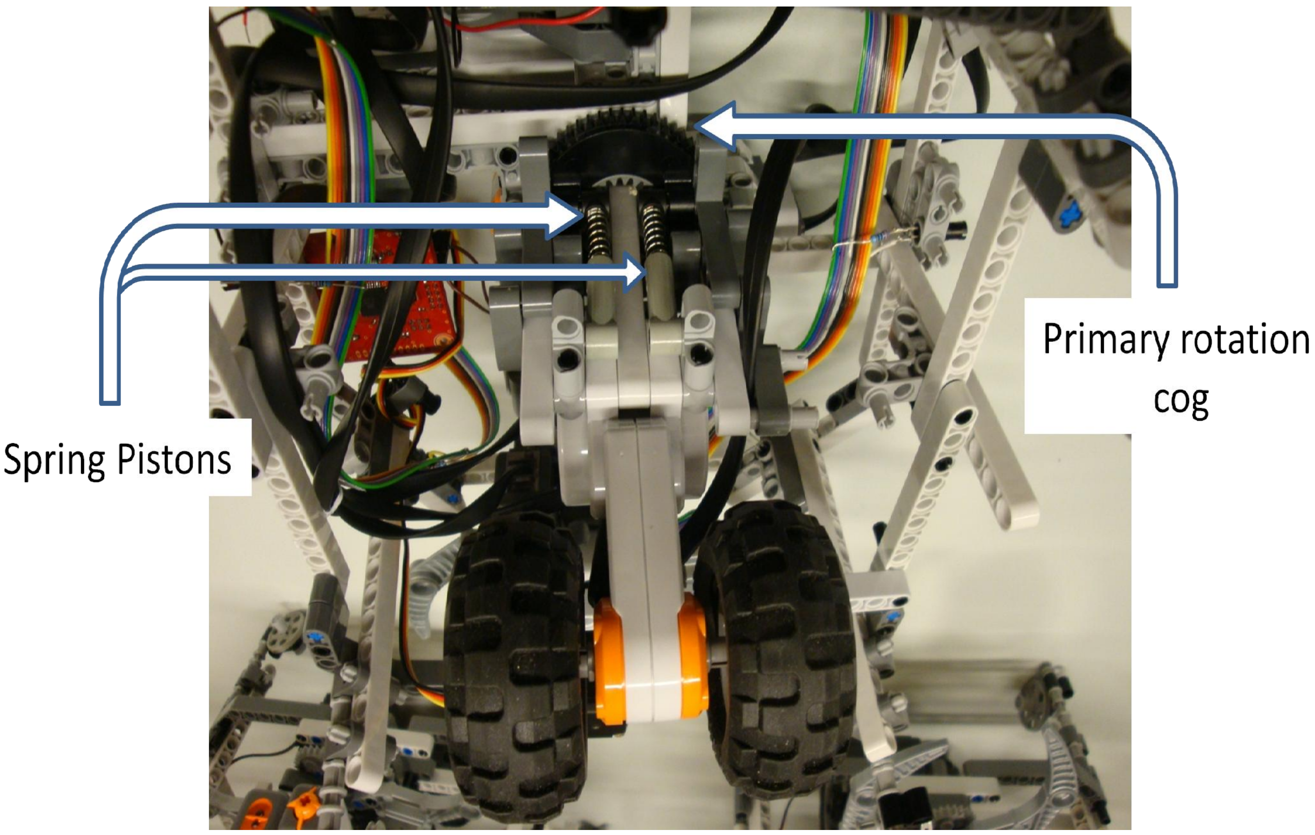

Fig. 23. Motion subsystem seen from bellow the unit, in this picture the *primary rotation cog* (black) can be seen on top of the spring pistons (gray and black) that support the actuator that has the tires attached to it to provide traction.

3.3.2 Outer Structure

The outer structure is like a shell built around the motion subsystem and contains all the environment sensing elements as well as the 7 LEDs and docking posts each one on one facet of the octagon) that allow the attaching of another unit here, as well as two actuators for motion control, sensors and the NXT unit. See Fig 24 for details. On the connection facet of the octagon, the gripper, ultrasonic, light and touch sensors are located all facing away from the unit (see Fig 24), and are used to detect and attach to another unit in the society as well as sense the environment while moving in it.

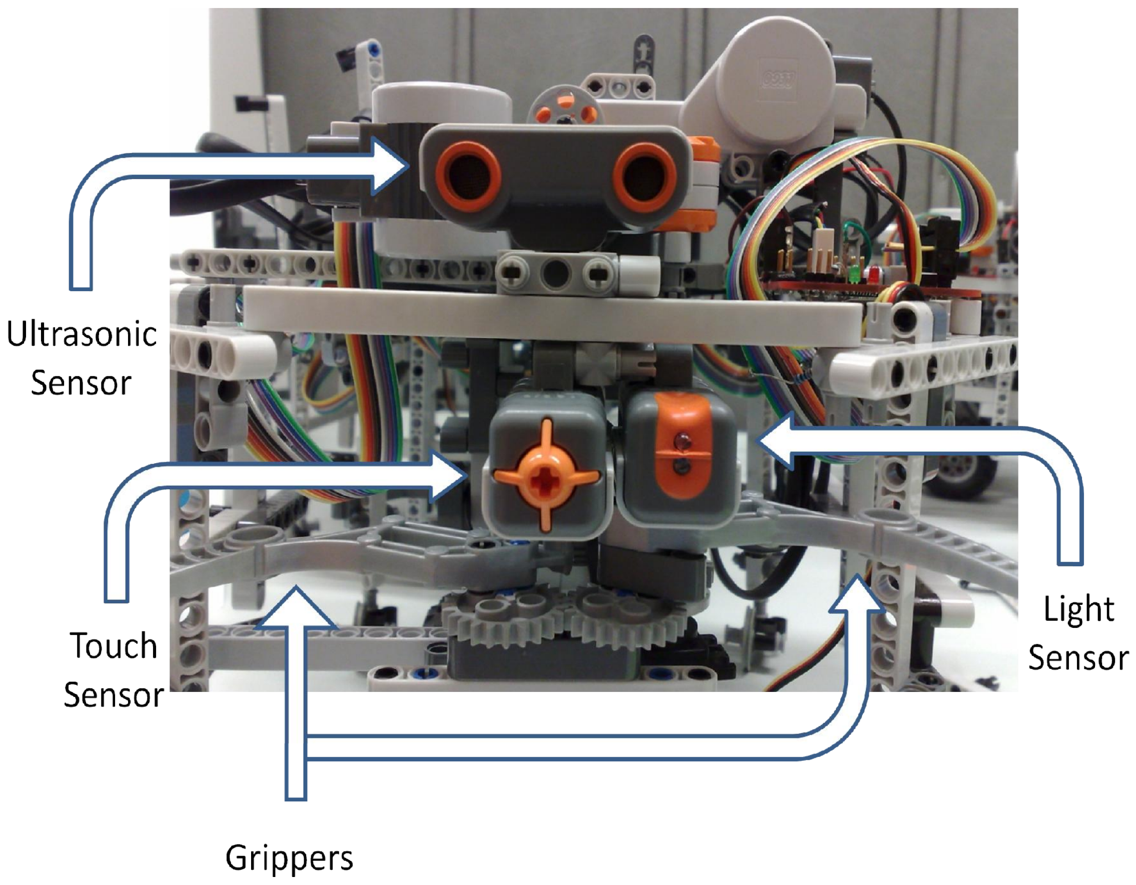

Fig. 24. View of the gripper, touch, light and ultrasonic sensors in the connecting facet of the octagon.

On four corners of the structure there are four loose tires (see fig 25).These loose tires are tires that have no traction and follow the structure like for example, shopping cart wheels, and are used to keep the stability of the structure was well as to follow the movement of the inner structure without resisting it and are also used as support for lifting the motion subsystem in order to steer as will be explained in section 3.4.

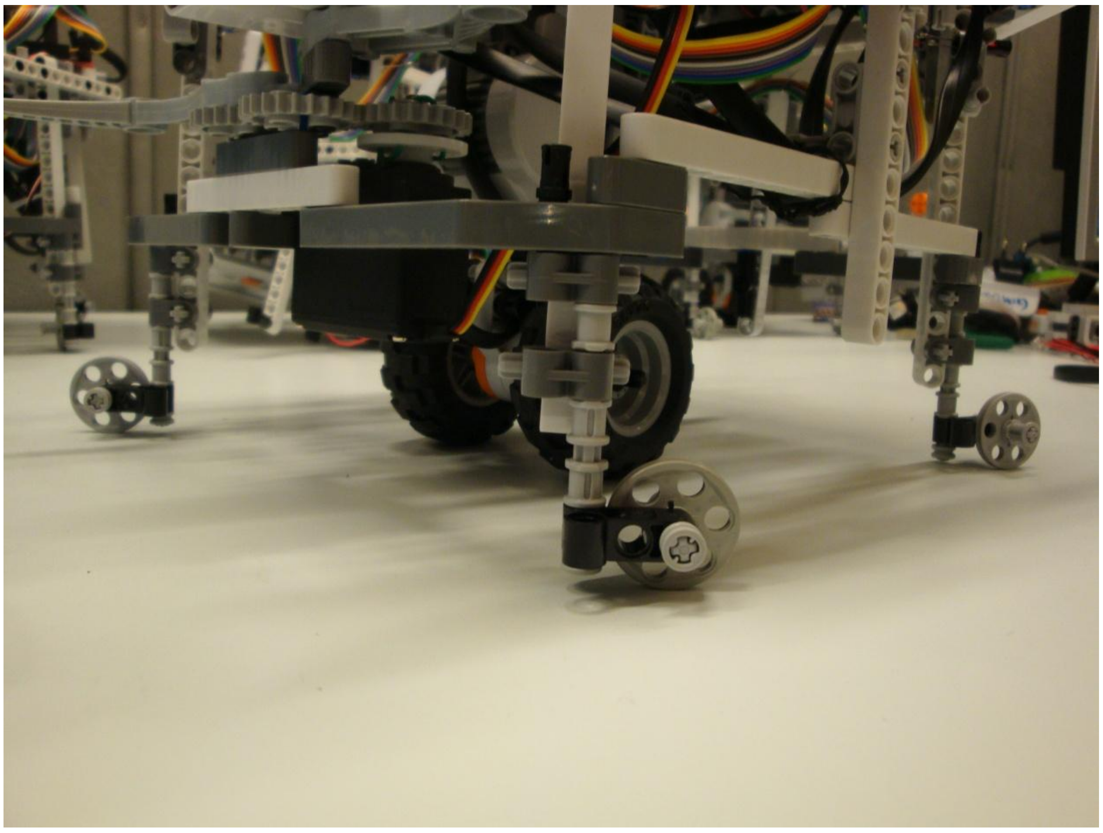

Fig. 25. Lower part of the unit showing the primary motion wheel and three of the four loose tires that provide stability and support when lifting the motion system.

In this structure there are two actuators in the top center of the unit. One is the one that moves the *primary rotation cog* to rotate the inner and outer structure with respect to each other, and the second one is used to lift and lower the inner structure, see Fig 26 for a picture of these actuators and their place in the system.

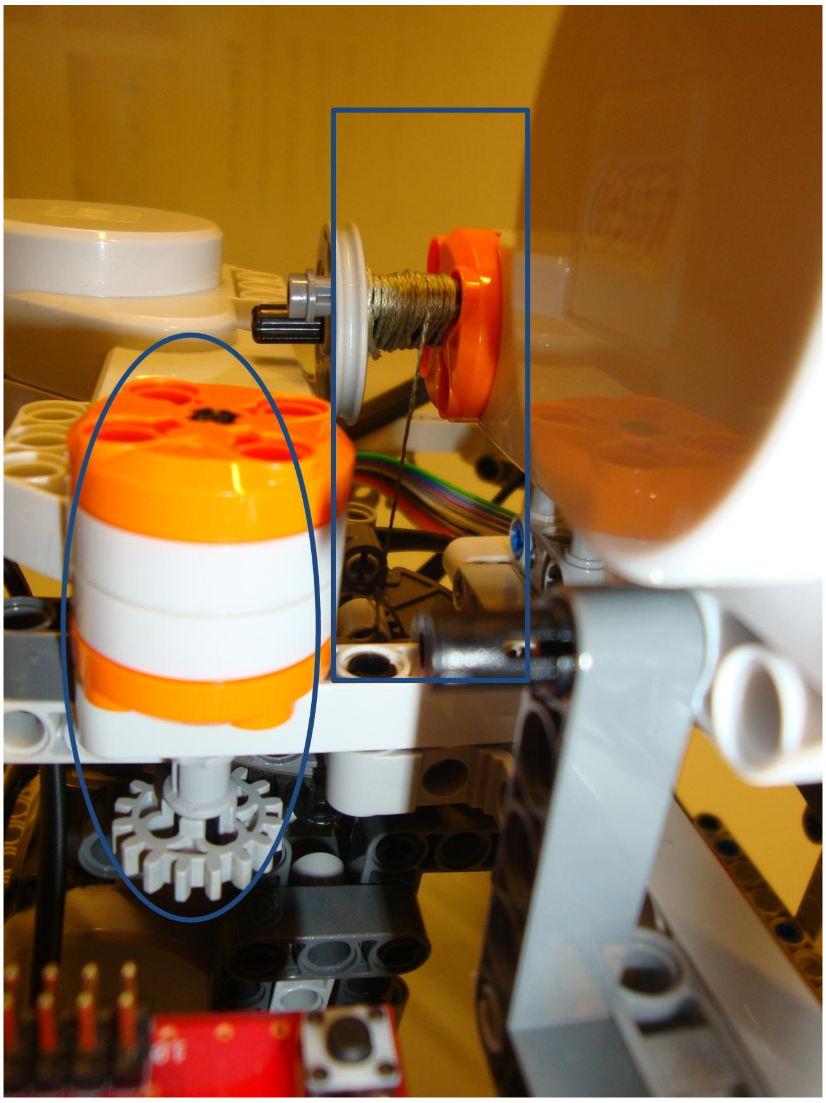

Fig. 26. Actuator in charge of lifting the motion subsystem with a tether (square) and actuator used to rotate the *primary rotation cog*.

3.4 Motion Technique

In this prototype a novel motion technique was developed using a single actuator for traction and two actuators to both steer the driving direction and change the orientation of the outer structure independently. This enables two or more units to be attached to each other and to steer their individual motion systems without putting any kind of stress in the link, this way avoiding any undesired change in the orientation of the joint structure that could occur while steering the individual motion systems. Units are also able to totally disable their motion system to let other units do the driving and save batteries without interfering or resisting the overall movement of the joint structure.

3.4.1 Modes of operation

As described in section 3.3.1 the motion system is comprised of a single actuator, and it can only move forward – backward, and is connected by a tether to another actuator (see Fig 23) used to switch between steering and structure rotation modes, both modes are described in the following subsections.

3.4.2 Steering mode

While the motion system is in its upmost position the tires attached to the movement actuator are not in contact with the ground, so the whole weight of the system is in the loose tires at the four corners. Now the motion system with its tires can be steered by rotating the *primary rotation cog*. In Fig 27 a steering sequence is shown by lifting the motion system and then rotating it 90^{o} before lowering it again.

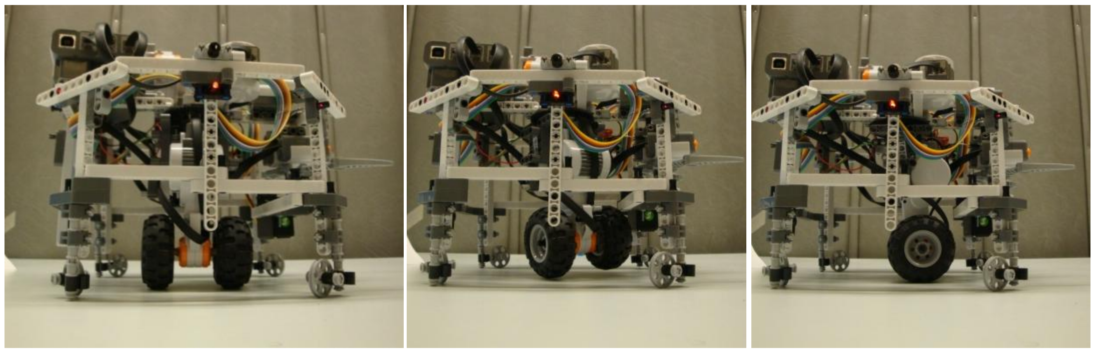

Fig. 27. Unit steering the motion system starting from pointing toward the reader (left) then lifting the motion system and turning counterclockwise (middle) and reaching 90o and lowering the motion subsystem (right).

3.4.3 Structure rotation mode

When the motion system is lowered the tires come in contact with the ground and the spring pistons put most of the unit's weight to the tires, so now in this configuration activating the *primary rotation cog* would result in making the structure rotate around the motion system and keep the steering direction firm when the motion system is in action. See Fig 28 for a structure rotation photo sequence.

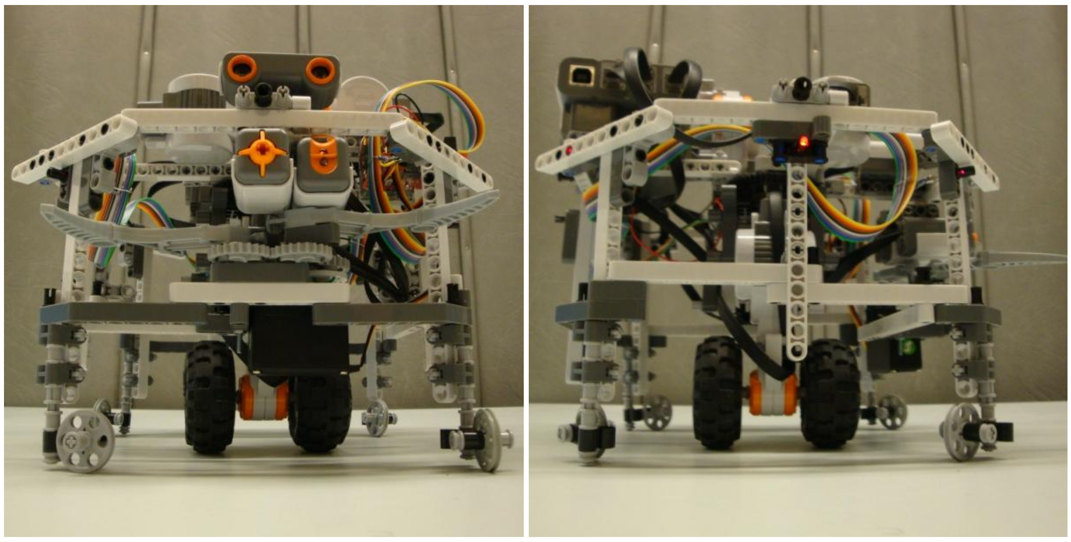

Fig. 28. Outer structure rotates 90^{o} around the motion system; this is done for reorienting the sensors and gripper, scanning with the sensors or reorienting the LED's orientation to try to make its position noticeable to other units nearby[1].

3.4.4 Motion routine

To drive around and orient the structure to the desired position motion routines were designed so that they always check the status of the rotation position state variable to never exceed the amount of degrees (+/- 180^{o}) that is safe to rotate one structure with regards to the other. This variable is in zero when both structures are aligned (starting

[1] To keep the cables from tangling and in this way preventing the *primary rotation cog* from rotating properly, and in worst case jamming it, the *primary rotation cog* should never rotate either the structure or the motion system more that +/- 180^{o} from each other. This safety measure is implemented in the motion routine and is described in the following section 3.4.2.

condition calibrated by supervisor) so if this rotation was requested that would exceed the safe values, the system would notice and calculate how to reach the same orientation by rotating in the opposite direction.

As an example if the outer structure is + 90^o displaced from inner structure and the units need to rotate the structure + 135^o instead of rotating + 135^o that would be closer to achieve (but it would take the displacement of structures to + 225) it would rotate – 225^o (displacement would be -135^o) this way reaching the same sensor orientation but without going over the 180^o safety displacement amount.

A similar procedure would be applied to change the driving direction, a difference in this case would be that if driving direction is more that 180o only change in forward - backward software would be needed and adjust the remaining degrees. As an example if again the inner and outer structure are displaced by + 90o and a change in direction of - 135 is needed. Instead of moving the -135 and exceeding the safety value it would rotate + 45 degrees and change the forward and backward direction convention, this way keeping the count of the displacement degrees in a safe value of + 45 and preventing the system from getting jammed or loose accuracy because of cog slippage.

Chapter 4

The Society: Definition, leader assignment and self-reconfiguration.

Probably the first and most important step of creating a society is creating a structure and the rules that the units will follow when a leader is to be assigned to take control of the available units and issue orders to achieve a task at hand, in this case, reconfiguration.

In this chapter a definition of Society will be presented, following by the leader assignment and reconfiguration algorithms created by the author in his efforts to start the foundations of a robot society.

4.1 Society definition

When many elements of similar characteristics are existing in the same area, they tend to form societies, it happens with most living organisms in the planet. It can be from very simple coexisting societies, where individuals hardly interact with each other, to very tightly cooperative complex societies that are usually conformed of a large number of individuals. A society as defined by Wikipedia is "… a body of individuals of a species, generally seen as a community or group that is outlined by the bounds of functional interdependence …"

In this robotic context a society will be defined as a group of robots working in a designated area that will discover the existence of more units of the same kind and try to communicate with them in order to work together.

4.2 Receiving Commands

There are two ways in which the society or single unit would receive a command to set a goal:

- When the system starts all the free units will be around looking to find a unit that has a task in order to be the Master of the system and start working. So when a new goal has been defined it will be send to a random unit, and by having a goal it will start recruiting units for achieving it
- Master units will be able to receive commands from a commanding unit[2] at all times, so a sequence can be aborted or to change the goal. To achieve this, the commanding unit connects to a random unit and asks for the Master name and network identifier, so it then connects to the master unit and issues the order.

4.3 Leader Assignment

The creation of the team is essential to having a group of autonomous robots that is versatile enough to choose it's team members, designate a leader, detect when units start malfunctioning or become lost (even the master), all this to make it autonomous in the sense that it will not require human intervention at the beginning of the life cycle, or when casualties occur.

Usually groups of robots start with pre-defined teams, and pre defined conditions that are usually handmade, which somewhat take away the autonomy of the system, that's why an effective dynamic way of forming and maintaining team of robots is necessary to be able to reach a state where the robots are truly autonomous and can handle unforeseen situations as well as perform new tasks that were not defined when the units where built.

[2] At this time, commanding unit means a Bluetooth-enabled computer that can send any unit in the society a command, but it is thought that in the future there could be other kinds of units in the society that have the task of, for example, be issuing orders, having a more advanced view of a more complex goal.

There has been some work before around this subject, in [7], a Pickup Team Challenge is proposed to deal with this critical problem that remains unsolved, and propose the treasure hunt domain for evaluating the performance of this pickup teams. This treasure hunt consists of heterogeneous units that need each other's abilities to be able to search for treasure so the Team member selection relies heavily in the fact that the units are heterogeneous, so this kind of approach would not work well in a small homogeneous society.

4.3.1 Implementation

As this society needs to have a temporal leader to coordinate all the units while working towards the goal. An algorithm to designate a leader among the units present in the working area was developed based on the ideas of the author and is the following:

As a free or master unit discovers other units close to it, it will pick the first one in its discovery list, connect to it and check its working status. It could be that the unit already is working for another Master unit; it is currently leading some units towards a task (is a Master) or it is operating alone. Depending on this unit status the unit asking will then either become master or slave of the newly discovered unit, or none depending on the case shown in Table 2.

Table 2. Leader assignment cases and their outcome according to the status of both the unit asking and the unit being asked.

Asking Unit Status (AU)	**Listening Unit Status (LU)**	**Result**
Working alone (with known task)	Working alone (with/ without known task)	AU becomes Master of LU
Working alone (without task)	Working alone (with known task)	LU becomes Master of AU
Working alone (without task)	Working alone (without task)	Both stay as Free units and continue to search for more units that could have a task.
Leading units[3]	Working alone (with / without known task)	AU becomes Master of LU
Working alone (with / without known task).	Leading units.	LU becomes Master of AU.
Working Alone.	Following another unit.	AU gets the name and network identifier of the master of LU and tries to locate it to ask to join.
Leading units.	Following another unit.	AU gets the name and network identifier of the master of LU to try to locate it and ask for status.
Leading Units.	Leading Units.	If working for the same goal the one more advanced in the reconfiguration process[4] will become the Master unit and will acquire the slaves[5] of the newly acquired unit. If they are both in the same stage the one having higher number of slave units will become the master unit and acquire the slave units of the other master.

[3] Leading units by default have a task defined.
[4] By more advance in the process it means that it requires less units to attach to the structure to reach the desired form or shape.
[5] Slave units will not be asking other unit's status.

4.4 Reconfiguration

4.4.1 Assembly

To get the units unto the desired configuration, the Master unit will move all the needed units to attach to the main structure until it is completed. To achieve this is will follow the following steps:

1. **Check** if there are units assembled and if the structure is reusable, this meaning that some units are connected in a position that will be useful to reach the desired configuration, if so those units will be retained and the rest will be ordered to detach and move away from the main structure.
2. **Prepare** the main structure to be able to rotate around its axis. This will be unique at every iteration of the assembly run as every time a unit is attached / detached the master unit needs to take into consideration all the tires of the attached units in order to choose the best motion technique[6] to make the structure rotate, and send the commands for the slaves to lift and rotate the tires accordingly.
3. **Point** any unit not in the main structure to be pointing in the main structure's direction. To achieve this, the master unit will make the main structure, that could be comprised of only the master unit, will turn all of its LED's on and start rotating around its axis, while having all the available free units rotate looking for the source of light, and when any particular unit has reached of bested the desired value in light intensity coming from the light sensor, all the rest will be ordered to stop moving and the main structure and the candidate unit will refine their position until the candidate is pointing straight to the main unit in the best possible angle.

[6] In this thesis work, the motion techniques are pre-defined to every step of the test reconfigurations, in future work an algorithm to calculate this motion according to structure would need to be designed.

4. **Align** the candidate unit to the desired hook up place. Now that the free unit is pointing towards the main structure in the best possible way, the main structure will now turn off all the LED's but the one in the place where it wants the candidate unit attached, and will rotate until the candidate unit reports to have the same value of light intensity coming from the light sensor as the one achieved in the Point step.
5. **Approach** the master unit will order the candidate unit to approach the main unit until it reaches hook up distance. The candidate unit will approach the main structure driving in a straight line while having the light sensor have the same or higher values than the ones acquired before until both the light and ultrasonic sensor confirm the unit is in the desired position. In case the light sensor stops detecting the LED, the unit will stop and report to the main unit, and in this case the main unit will start turning the structure in an oscillatory motion until the candidate detects the LED again so it can resume its approach.
6. **Hook Up** to the main structure by closing the linking tool until it firmly grasps the connection point.

These steps will be repeated until the desired shape has been assembled or there are no more available free units in the vicinity of the main structure.

4.4.2 Coordination

After all the units have been placed in the correct configuration by the Master, the Master will coordinate all the units to move their tires to point in the same direction to be able to move as a whole using as many motors as needed and putting the remaining motors in neutral or lifting them to save energy.

At the point of completion of this thesis work, the tires of the two units closer to the center of rotation where lifted and the remaining two units will use their motion systems to drive the big unit like a tank using skid steering.

Chapter 5

Tests

5.1 Tests and Results

The following subsections will describe the tests that were performed on the motion subsystem, the light sensor sensibility to the LED's light, the light sensor sensibility to laser pointers' light, the Leader Assignment algorithm and the reconfiguration algorithm.

5.1.1 Motion Subsystem: rotating structure

The first tests made were to refine the rotation between the *Motion Subsystem* and the *Outer Structure* and to find the safe area in which the primary rotation cog could rotate freely without getting stuck.

For this test simple routines were programmed to remote control the motors from LabVIEW and were tested an all four readily assembled units.

Results

After calibrating all units and making some changes to the mechanical structure, all four units were able to rotate the Outer Structure +/- 180 degrees from the Motion Subsystem without getting stuck.

5.1.2 Motion Subsystem: driving

Motion routines were implemented according to the Motion Routine described in section 3.4 to test that the unit could move around an area with a the combination of the three main actuators. The following routines were implemented on all four units:

- **Rotate Right:** This routine would rotate the *outer structure* 90^o from the *motion subsystem* using the *primary rotation cog* in a clockwise direction (as the motion subsystem is in contact with the ground the structure rotates and the *motion subsystem* remains static), then lift the motion subsystem by rotating the lifting actuator 180^o, rotating again the *outer structure* 90^o from the *motion subsystem* using the *primary rotation cog* in a clockwise direction (as the motion subsystem is not in contact with the ground the structure remains static and the *motion subsystem* rotates freely) and then rotating the lifting actuator -180^o to lower the *motion subsystem* and be in the same configuration as in the beginning but facing both *outer structure* and *motion subsystem* 90^o from the initial position.
- **Rotate Left:** The same as Rotate Right but rotating the *primary rotation cog* in counter-clockwise direction.
- **Move Forward**: Rotate the *motion subsystem* actuator that is attached to the tires' "forward".
- **Move Backward**: Rotate the *motion subsystem* actuator that is attached to the tires' "backwards".

Results

By using these routines the system was tested and the height of the four loose tires that support the outer structure with regards to the ground was calibrated to its optimal state. Also the system was debugged and some minor hardware changes were made to allow the system to perform these tasks.

5.1.3 Expansion Board: operation of LEDs

Sample routines were created to test that the operation of the LEDs matched the desired functionality, and that the software written for the ATMEGA164P was working properly when integrated into the system.

Results

Both the LabVIEW routines and the software to run the ATMEGA164P were debugged in these tests and as a result LabVIEW virtual instruments were created to turn the LEDs ON and OFF via I^{2}C. Also the LED and I^{2}C routines in the ATMEGA164P were finalized.

5.1.4 Expansion Board: Gripper movement

Sample routines were created to test that the operation of the Servo control matched the requirements, and that the software written for the ATMEGA164P was working properly when integrated to the system.

Results

The routines for moving the servo motor by changing the duty cycle of the PWM signal as described by section 3.1.8 were working properly and the final version of the code for the ATMEGA164P was finalized and uploaded to all Expansion Boards.

5.1.5 Leader Assignment

The leader assignment algorithm was implemented as set of LabVIEW virtual instruments as was tested independently from all other software. In this subsection tests and results for this algorithm will be shown.

A set of two LabVIEW virtual instruments (.vi files) were implemented to test the Leader Assignment algorithm. LAF.vi was run in units with the role of “Free units”, and LAM.vi was run in the “Master units” (see appendix E.1 for the software implementation of LAF), and tests were made with units in different stages with the following results:

- All “Free” units without task were running the same software LAF and they scanned all units, and at the end they all remained free units.
- Three Units were “Free” running LAF.vi and one was “Master” running LAM.vi, at the end of the run the “Master” remained being Master and the three “Free” units had “Slave” status with the Master’s id on the file “MasterID”.

- One “Free” unit running LAF connected to a “Slave” (slave units are not looking for more units because they already have a Master) and got the ID of the Master.

5.1.6 Reconfiguration

To be able to test the reconfiguration algorithm, virtual instruments Slave.vi and Master.vi were developed to test the approach of a unit by command of the Master unit, and then closing the gripper to link (see appendix E.2 for the software implementation of Slave.vi).

Results
Extensive testing had to be performed in different natural lighting conditions, as the light sensor was not behaving as expected. In regular daylight conditions the algorithm acted erratically as the light sensor was heavily influenced by the natural light from the windows and the room lamps. In dark room conditions during nighttime, results improved quite drastically, which led to performing tests 5.1.7 to 5.1.10.

5.1.7 Light sensor sensibility to LED light: Normal room light conditions

A LabVIEW routine was implemented to be able to see the intensity of the light detected by the light sensor in real-time plotted on a scope and see the difference in intensity with regards to distance.

This test consisted on having two units standing one behind the other with the light sensor one centimeter away from the back side LED of the unit on front, and then having the unit in front move forward 20 centimeters using the move forward routine, and record the readings. In Fig. 29 the start and end conditions can be appreciated as well as a close-up of the LED being in front of the light sensor.

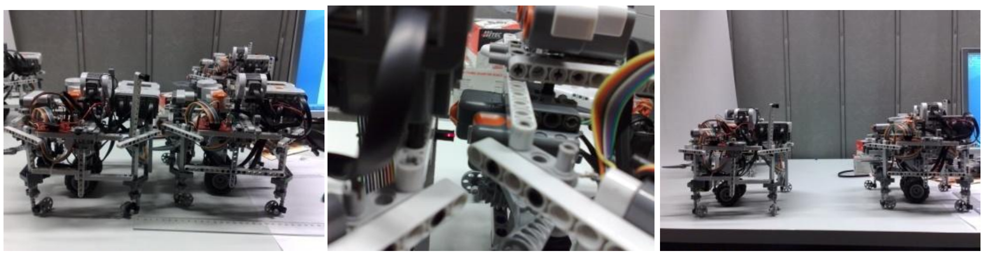

Fig. 29. The start condition seen from the side of both units (left), a close up of the LED being 1 cm in front of the light sensor (center), and the end condition of both units (right) while performing the test 5.1.7.

Results

The readings were recorded and are shown in Fig. 30, where we can see the raw values received from the light sensor while running the test and seeing that at the start the raw value received by the sensor is of about 620 units in point 1, and then when the unit moved to be 20 centimeters farther the reading became around 700 units in point 2, and is about the regular value of the room as can be seen when the LED light is blocked from the sensor in point 3.

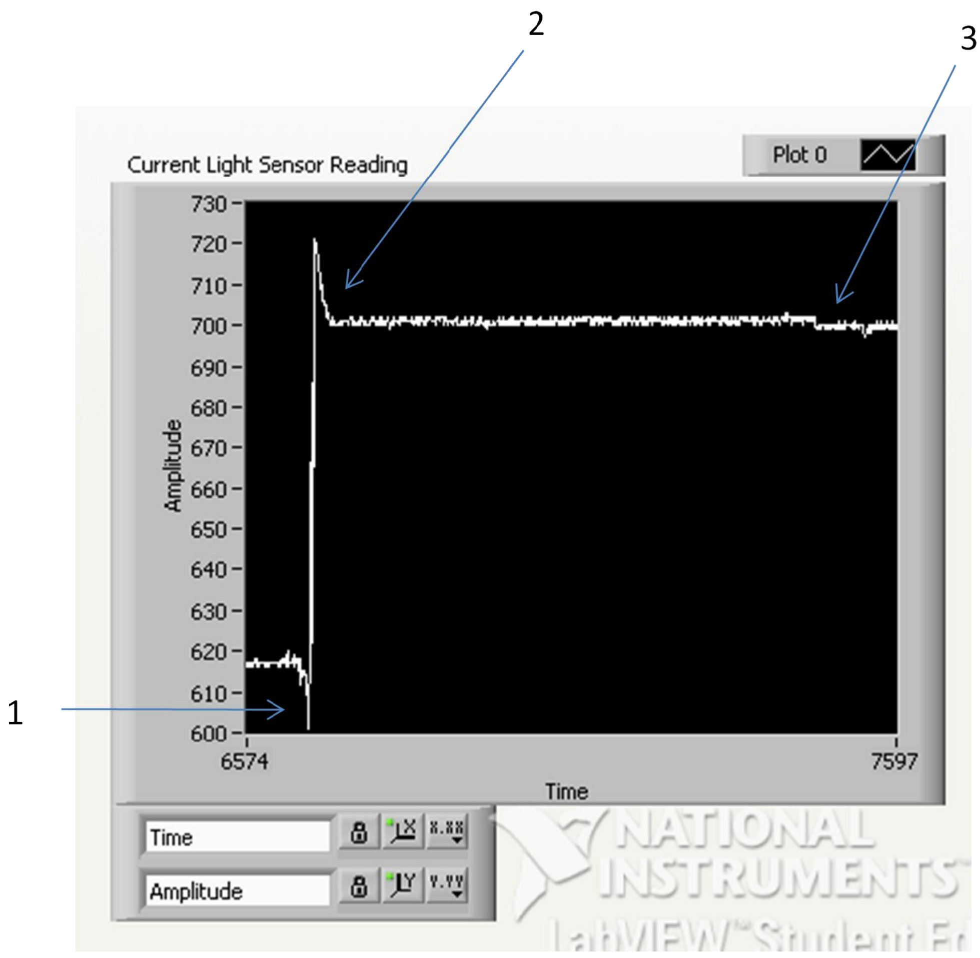

Fig. 30. Raw light sensor readings from the light sensor pointing straight to an LED 1 cm. away (1), when the unit moved 20 cm away (2) and when the LED's light was blocked (3).

5.1.8 Light sensor sensibility to LED light: Dark room

Test similar to the one in 5.1.7 with the difference that it was done with the lights of the room off, and as all the tests took place at midnight (00:00 am), the room was as dark as possible.

Start conditions were the same and can be seen in Fig. 31, where the upper left picture is the starting position without camera flash, lower left is at the same position with camera flash, upper center is LED in front of the light sensor without camera flash, lower center same position with camera flash, and right picture is ending position with camera flash.

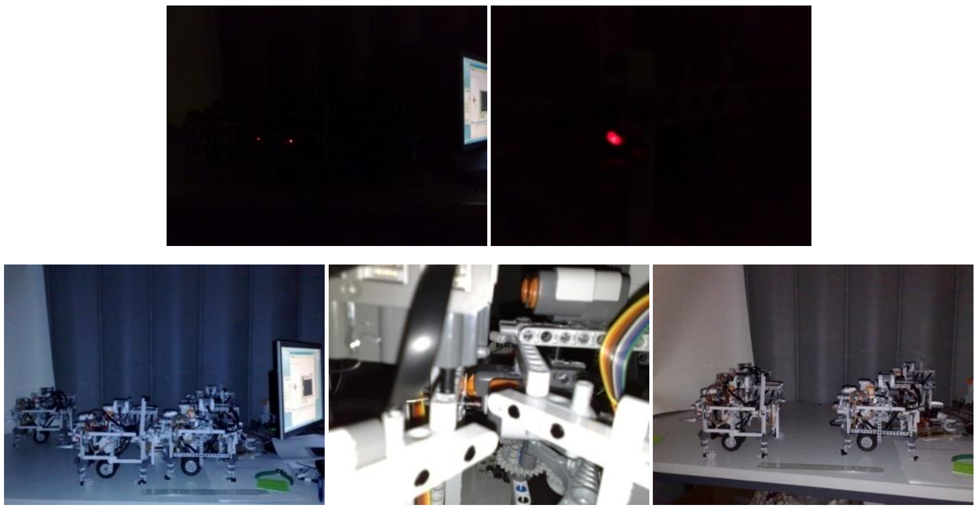

Fig. 31. The start conditions seen from the side of both units (left, upper without and lower with camera flash), a close up of the LED being 1 cm in front of the light sensor (center, upper without and lower with camera flash), and the end condition of both units (right) while performing the test 5.1.8. in dark room conditions.

Results

The readings were recorded and are shown in Fig. 32, where we can see that the start the raw value received by the sensor is of about 575 units in point 1, and then when the unit moved to be 20 centimeters farther the reading became around 870 units in point 2, and when the LED light is blocked from the sensor in point 3 the value becomes 875, and the last point is where the LED was uncovered again and the unit with the light sensor turned 45 degrees clockwise to point into a dark area that has around the same value as 875, but been reached gradually as the unit rotates to point away.

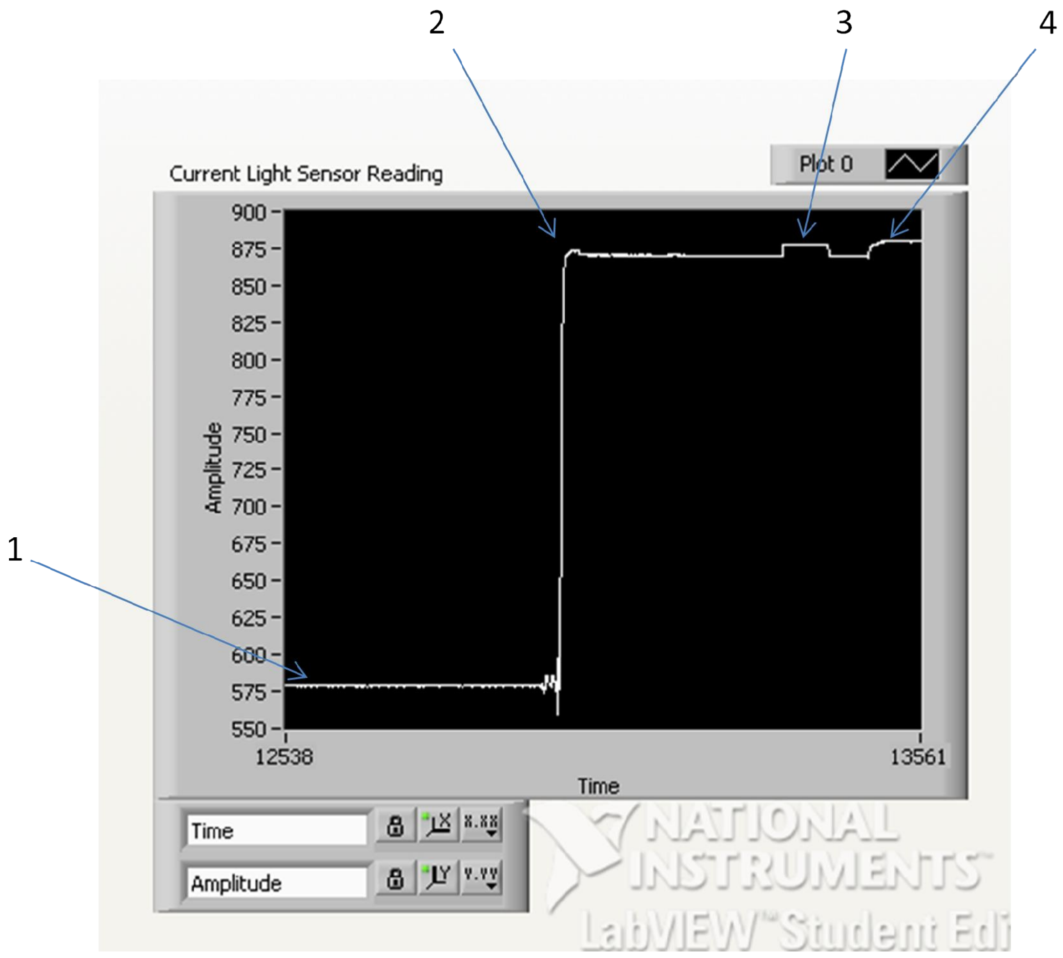

Fig. 32. Raw Light sensor readings from the Light sensor pointing straight to an LED 1 cm away (1), when the unit moved 20 cm away (2), when the LED's light was blocked (3), and when unit using the light sensor rotated to point a dark location (4).

5.1.9 Light sensor sensibility to Laser Pointer light: Normal room light conditions

Test similar to 5.1.7 in lighting conditions, with the difference that in this test, instead of the LED light mounted on a STORM unit, the test would be done with a laser pointer at about the same height so that the its light would hit straight into the light sensor. In Fig. 33 the setup with the starting and ending conditions and the close-up of the laser pointing directly into the light sensor can be seen.

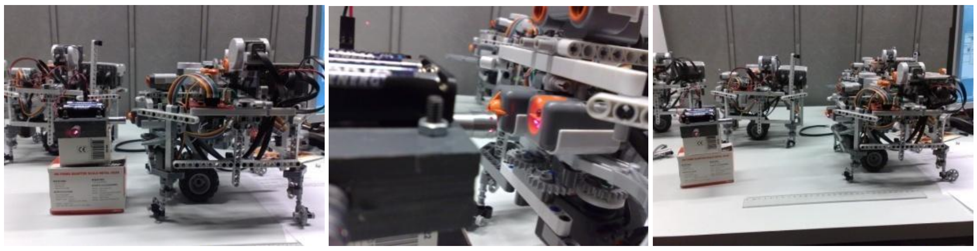

Fig. 33. The start condition seen from the side of both units (left), a close-up of the laser pointer being 1 cm. in front of the light sensor (center), and the end condition of both units 20 cms. from each other (right) while performing the test 5.1.9. in normal room illumination conditions.

Results

The readings were recorded and are shown in Fig. 34, where we can see the raw values received from the light sensor while running the test and seeing that at the start the raw value received by the sensor is of about 100 units in point 1, and then when the unit moved to be 20 centimeters farther the reading stayed around 100 units in point 2 (some amount of noise can be seen because of the movement to move the laser pointer 20 cms. away), in point 3 the laser pointer light is blocked and the value raised to around 720 units, and then the laser light is unblocked again so that then the unit can turn around 45 degrees into common room lighting in point 4, that comes to around 700 units.

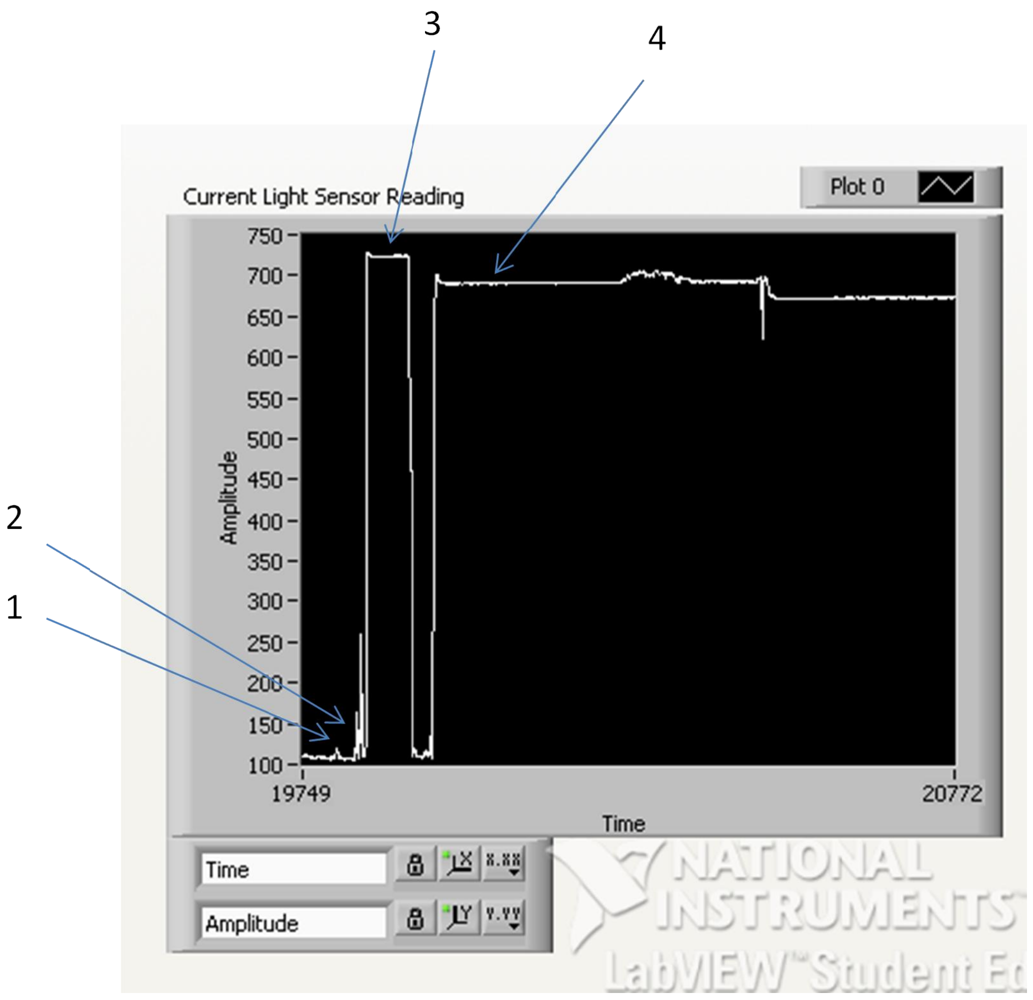

Fig. 34. Raw Light sensor readings from the light sensor pointing straight to the laser pointer 1 cm away (1), when the laser pointer was moved 20 cm away (2), when the laser pointer's light was blocked (3) and when unit using the light sensor rotated to point a non-laser common-lighted room location (4).

5.1.10 Light Sensor sensibility to Laser Pointer light: Dark room conditions

Test similar to the one in 5.1.9 with the difference that it was done with the lights of the room off, and as all the tests took place around midnight (00:00 am) the room was as dark as possible. In Fig. 35 the setup with the starting and ending conditions and the close-up of the laser pointing directly into the light sensor can be seen, only this time the pictures were taken in the dark room with the camera flash activated.

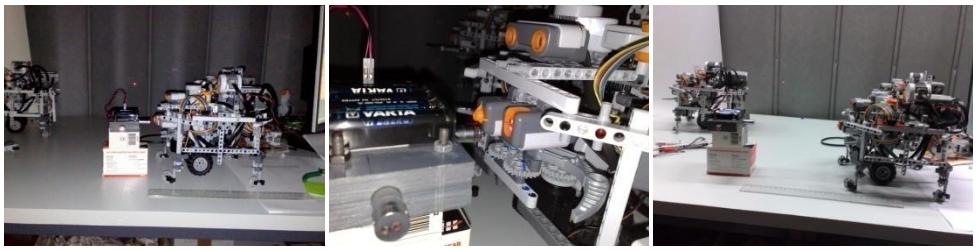
Fig. 35. The start condition seen from the side of both units (left), a close-up of the laser pointer being 1 cm in front of the light sensor (center), and the end condition of both units 20 cms from each other (right) while performing the test 5.1.10. in dark room conditions.

Results

The readings were recorded and are shown in Fig. 36, where we can see that the start the raw value received by the sensor is of about 100 units in point 1, and then when the unit moved to be 20 centimeters farther the reading stayed in 100 units, just there was some small noise that had to do with the moving of the laser as shown in point 2, and when the LED light is blocked from the sensor in point 3 the value becomes 875, and the last point is where the LED was uncovered again and the unit with the light sensor turned 45 degrees clockwise to point into a dark area with the same value 875 in point 4, that is reached with some noise but in a shorter time with a steeper change of values.

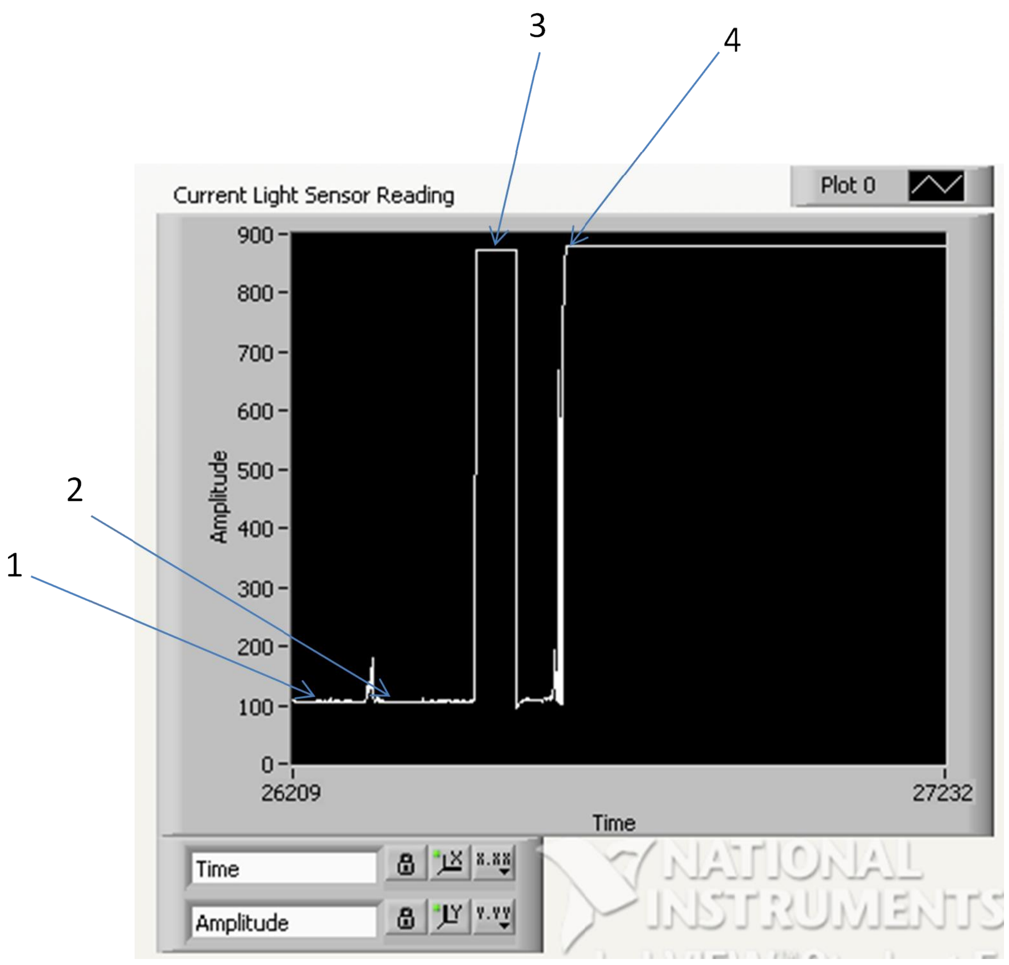

Fig. 36. Raw light sensor readings from the light sensor pointing straight to the laser pointer 1 cm away (1), when the laser pointer was moved 20 cm away (2), when the laser pointer's light was blocked (3) and when unit using the light sensor rotated to point a non-laser dark location (4).

5.2 Conclusions on the results and future work

The implementation of the Leader Assignment algorithm in LabVIEW proved to be a good way to designate a leader based on a case structure with all the possible options, and units clearly behave respond the way they should. It was tested with the four units that were constructed and in the different roles and stages. For future work it would need to be tested on a larger scale system and add priorities among Heterogeneous units for example.

While implementing the reconfiguration algorithm it was proven that this approach could provide a viable solution, if better LED lamps and/or sensors are used. The major problems were that it was designed under the assumption of an ideal, noise-free environment and the sensitivity of the light sensor was overestimated. Many tests were done, but the light sensor proved to be very sensitive to ambient noise such as natural outside light as well as white light from the room lamps and a combination of this problem with the LED lamp's diffused light beam took a high toll on the system. The best results with the LED's were acquired late at night with the system in total darkness, and even then the LED's 50^o viewing angle make the system perform poorly in the approach when the distance is greater than 20 cms. The results of the tests 5.1.9 and 5.1.10 show clearly that the laser beam from the laser pointers is perfectly identified by the light sensor but has to be pointing directly into the sensor to be successful. For future work trying more powerful LED lamps with smaller viewing angle or adapting laser pointers to be integrated into the system is necessary. Also, adding more LEDs and/or the use of color coding as seen in Swarmbots [8] would definitely improve the existing system. Fusing the sensor information of the ultrasonic sensor with the light sensor could also improve the unit's ability to attach successfully.

Chapter 6

Previous Prototypes

Before reaching the actual design, many prototypes with different functionality were built and tested, but were discarded due to a major problem mostly in the physical implementation, the two most important ones are described in this chapter, their concept and more importantly why there were abandoned.

6.1 1st prototype, “worms / snakes”

The first prototype was intended to have worm-like units that would have 3 degrees of freedom and would have slots all over the body so another unit could attach to it by knowing the orientation of a certain unit regarding the others. Each unit could attach / detach from another with the male connectors in the front or back (or the “head and the tail) and attach to the female connectors all over the sides of other unit, see Fig 37 for details.

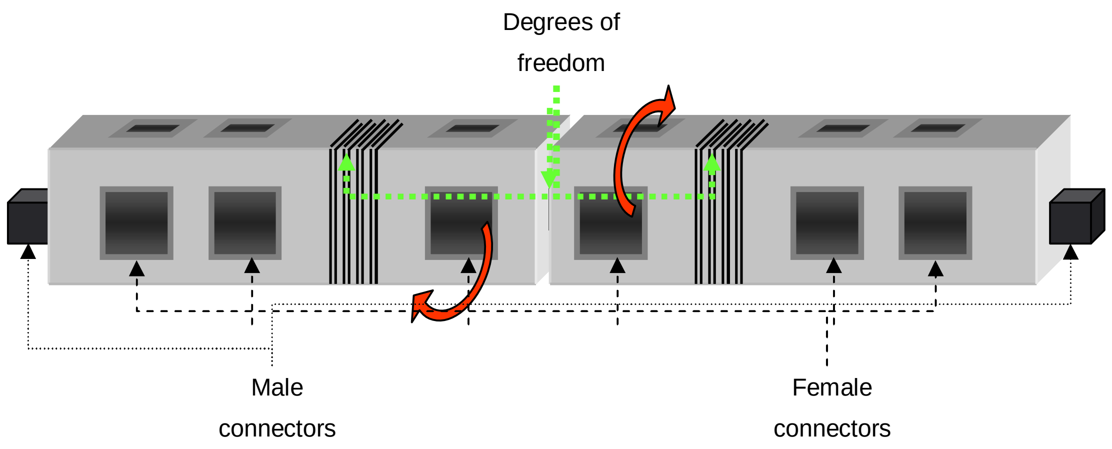

Fig. 37. Worm unit with its male connectors, female connectors and three degrees of freedom.

Using geometry and the three degrees of freedom, the unit would move from one slot to the next and reach the desired position. In Fig 38 two units are connected, the "n" shaped unit on top has both its male connectors attached to the female connectors of the unit that is totally straight.

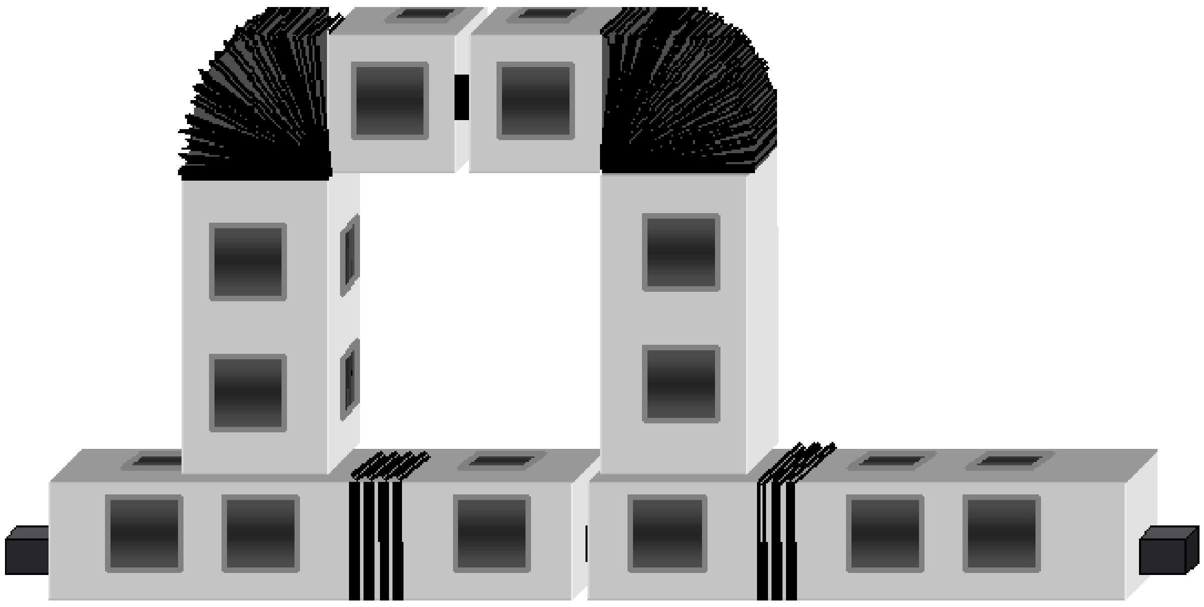

Fig. 38. Example of two units attached to each other.

This system was intended to have the capability to morph the system into a four-legged walking robot like the one illustrated in Fig. 39.

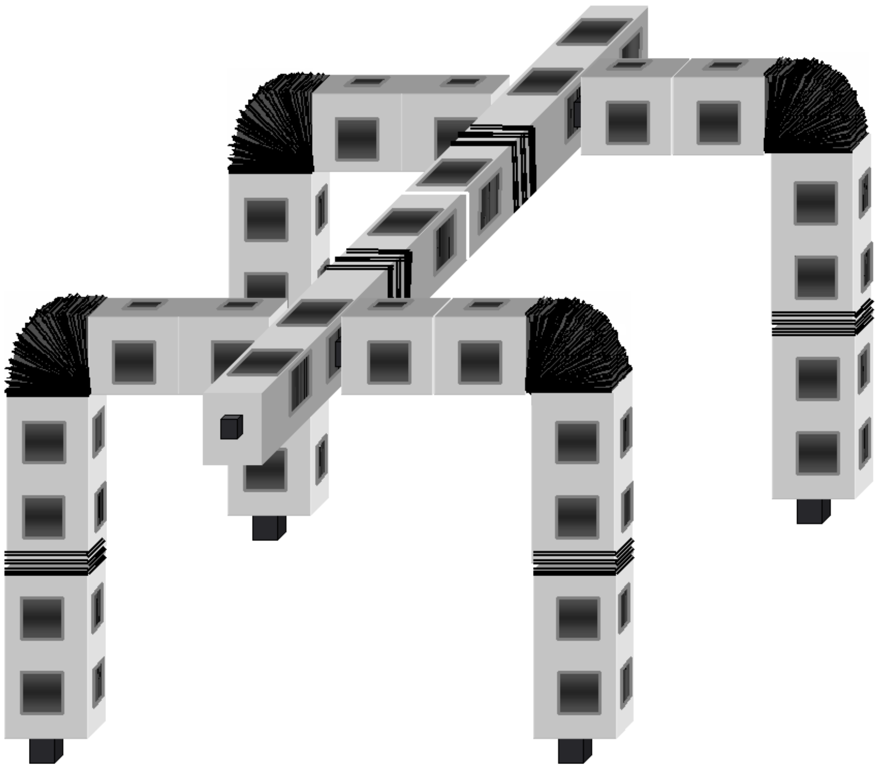

Fig. 39. Prototype 1 morphed into a four legged walker.

6.1.1 Planned Control

The control of this society was planned to be using the control theory of robotic arms, using link matrixes per every degree of freedom and calculate the transformation matrix for every movement, and even Jacobians to control the velocities as described in [15]. Although heavy to process, the NXT units could handle them.

6.1.2 Problems

While building this prototype, many problems arose regarding the physical implementation as the NXT module and the actuators are very big. Therefore, the resulting unit needed to be very large in order to have the necessary length to width/height size ratio. Another problem was that to be able to connect the unit from both ends, too many sensors and extra motors were needed, as building a connector with this functionality is very complex.

6.2 2nd prototype, “Tiles”

The second prototype was designed to have units in the form of square tiles with two male and two female connectors each. In Fig. 40 these connectors are shown, the hollow gray squares are the female connectors and the filled gray squares are the male connectors.

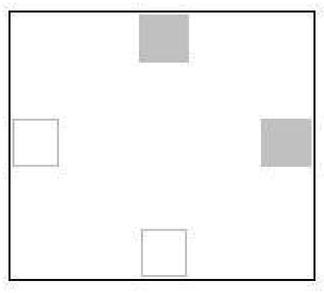

Fig. 40. Prototype 2 and its connectors.

These units would connect the male connector to the female connector of a surrounding unit and then pull the connector back to make bring the two units together along with other units that could be attached to other connectors on any of the two units. As an example, in Fig 41 there is a sample sequence of how the units could move in the horizontal plane, here the black figures indicate a male connector bound to a female one.

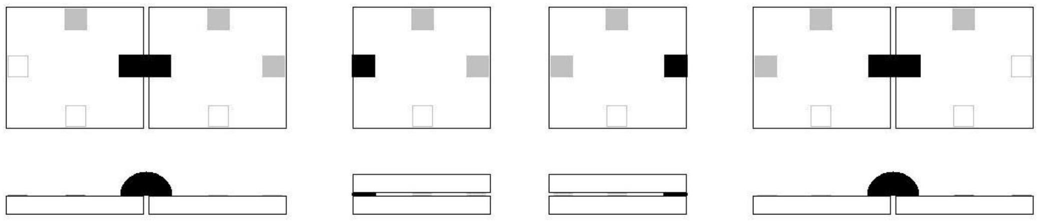

Fig. 41. A Sequence of how prototype 2 units would move as seen from the top (above) and from the side (below).

Having a large number of tile units would allow the system to move around a physical area regardless of the shape of the terrain, and to climb obstacles larger in size than a single unit, as shown in Fig. 42

.

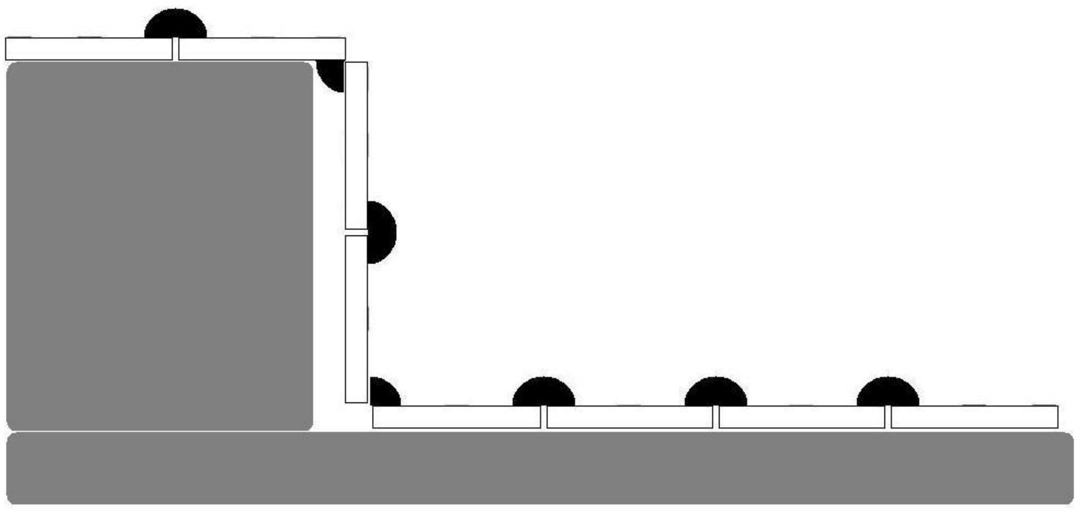

Fig. 42. A group of Tile units that reconfigured themselves to climb over an obstacle, all male connectors working on a 180^o link.

6.2.1 Planned Control

This society would also be controlled by the master by the use of transformation matrixes and Jacobians as the 1st prototype in the last chapter..

6.2.2 Problems

This prototype’s first major problem came when trying to make the male connectors be able to push the link beyond 265^{o} as the connector had to be very large and with some sort of telescopic expandable / retractable mechanism, that proved to be very difficult to achieve with Lego Mindstorms equipment.

The second problem arose when trying to make the link have more than one unit “in the air”, that is, to be moving more than two units up from the ground to, for example, try to reach on top of an obstacle. When trying this configuration, the links involved had too much tension and the Lego pieces began to separate as the weight of the two units was too much for the structure to bear without disassembling. The motors could easily lift the weight but the structure was unable to stand in mid air in a stable condition, to do so would require a lot more pieces to be attached, and the system’s weight would increase in a manner that the problem would be unsolvable with the available equipment. Because this would be needed for the system to be able to reach its designed goals the prototype had to be abandoned.

Chapter 7

Conclusions

Right now there are some systems that have been able to achieve solid goals, like *Stochastic 3D, M-Tran, Molecubes and Swarmbots* that, each in their own categories, will surely become cornerstones in fulfilling the promise of one day becoming: *Versatile*, *Robust* and *Low Cost* systems, and by doing so they will have a great impact everywhere, especially in the areas of:

- **Space Exploration:** having less amount of mass sent up, and being able to use it in so many ways (as the units will be able to adapt and do tasks not foreseen before they happen) will definitely be a boost.
- **Pollution / Environmental**: Having a single system instead of more and more robots for all the different needs, will definitely impact in needing less and less resources from our planet being consumed as well as saving energy too. In addition to the growing problem of saturating our living spaces with more and more machines lying around, which will eventually lead us to have even traffic control systems in our own homes.

Creating a robot society is very complex and time consuming, especially because is an area of robotics that it's on the early stages of development. With this thesis work, creating a prototype society made of LEGO Mindstorms was achieved successfully, and although some problems arose and the system could not self-reconfigure itself with high accuracy as it was desired, some good results have come from it, such as:

- Prototyping with LEGO Mindstorms is a fast way to prototype mechanical systems and, with basic algorithms test the viability and stability of the system in order to be able to decide if to continue to put more time effort and money on the proposed design, to know the areas where more improvements are needed, or if to totally abandon the idea.
- The Lego Mindstorms NXT's set can be upgraded with the expansion board and many sensors and / or motors can be easily added so the system is not fully dependant on LEGO's constrains and specifications.
- The single traction motion technique described in section 3.4 was tested and showed to be a good option to use with reconfigurable systems that need to have the structure independent from the traction.
- The Leader assignment algorithm was successfully implemented in LabVIEW and could be the base of a more complex leader assignment algorithm for Heterogeneous societies.
- Initial testing was done on the approach for mobile reconfiguration and with proper upgrades the system could have a bright future.
- The robot society was used to test the coordination algorithms of Jürgen Leitner's thesis work [17], and took part of the Multi-robot Teaming challenge of the International Joint Conference on Artificial Intelligence (IJCAI - 09) [18].

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Appendix A

TWI Communication Protocol from ATmega164P datasheet

19. 2-wire Serial Interface

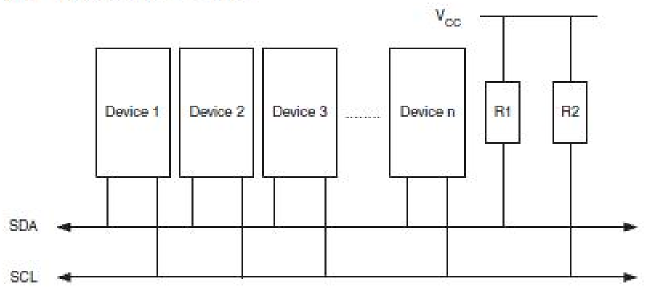
19.1 Features

- **Simple Yet Powerful and Flexible Communication Interface, only two Bus Lines Needed**
- **Both Master and Slave Operation Supported**
- **Device can Operate as Transmitter or Receiver**
- **7-bit Address Space Allows up to 128 Different Slave Addresses**
- **Multi-master Arbitration Support**
- **Up to 400 kHz Data Transfer Speed**
- **Slew-rate Limited Output Drivers**
- **Noise Suppression Circuitry Rejects Spikes on Bus Lines**
- **Fully Programmable Slave Address with General Call Support**
- **Address Recognition Causes Wake-up When AVR is in Sleep Mode**

19.2 2-wire Serial Interface Bus Definition

The 2-wire Serial Interface (TWI) is ideally suited for typical microcontroller applications. The TWI protocol allows the systems designer to interconnect up to 128 different devices using only two bi-directional bus lines, one for clock (SCL) and one for data (SDA). The only external hardware needed to implement the bus is a single pull-up resistor for each of the TWI bus lines. All devices connected to the bus have individual addresses, and mechanisms for resolving bus contention are inherent in the TWI protocol.

Figure 19-1. TWI Bus Interconnection



19.2.1 TWI Terminology

The following definitions are frequently encountered in this section.

Table 19-1. TWI Terminology

Term	Description
Master	The device that initiates and terminates a transmission. The Master also generates the SCL clock.
Slave	The device addressed by a Master.
Transmitter	The device placing data on the bus.
Receiver	The device reading data from the bus.

The Power Reduction TWI bit, PRTWI bit in "PRR – Power Reduction Register" on page 47 must be written to zero to enable the 2-wire Serial Interface.

19.2.2 Electrical Interconnection

As depicted in Figure 19-1, both bus lines are connected to the positive supply voltage through pull-up resistors. The bus drivers of all TWI-compliant devices are open-drain or open-collector. This implements a wired-AND function which is essential to the operation of the interface. A low level on a TWI bus line is generated when one or more TWI devices output a zero. A high level is output when all TWI devices trim-state their outputs, allowing the pull-up resistors to pull the line high. Note that all AVR devices connected to the TWI bus must be powered in order to allow any bus operation.

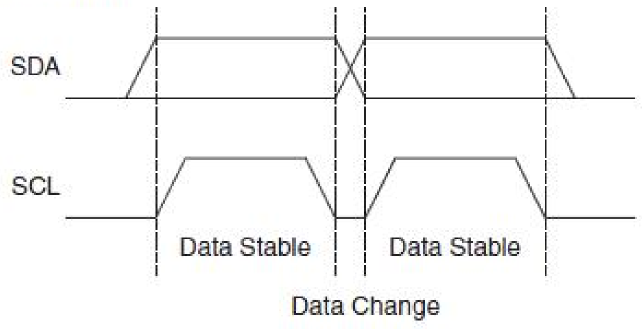
The number of devices that can be connected to the bus is only limited by the bus capacitance limit of 400 pF and the 7-bit slave address space. A detailed specification of the electrical characteristics of the TWI is given in "SPI Timing Characteristics" on page 333. Two different sets of specifications are presented there, one relevant for bus speeds below 100 kHz, and one valid for bus speeds up to 400 kHz.

19.3 Data Transfer and Frame Format

19.3.1 Transferring Bits

Each data bit transferred on the TWI bus is accompanied by a pulse on the clock line. The level of the data line must be stable when the clock line is high. The only exception to this rule is for generating start and stop conditions.

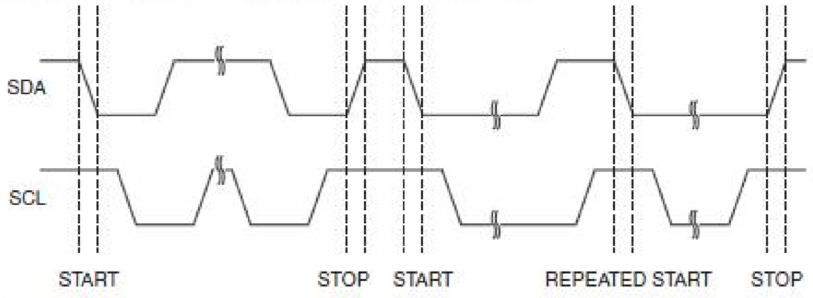
Figure 19-2. Data Validity



19.3.2 START and STOP Conditions

The Master initiates and terminates a data transmission. The transmission is initiated when the Master issues a START condition on the bus, and it is terminated when the Master issues a STOP condition. Between a START and a STOP condition, the bus is considered busy, and no other master should try to seize control of the bus. A special case occurs when a new START condition is issued between a START and STOP condition. This is referred to as a REPEATED START condition, and is used when the Master wishes to initiate a new transfer without relinquishing control of the bus. After a REPEATED START, the bus is considered busy until the next STOP. This is identical to the START behavior, and therefore START is used to describe both START and REPEATED START for the remainder of this datasheet, unless otherwise noted. As depicted below, START and STOP conditions are signalled by changing the level of the SDA line when the SCL line is high.

Figure 19-3. START, REPEATED START and STOP conditions



19.3.3 Address Packet Format

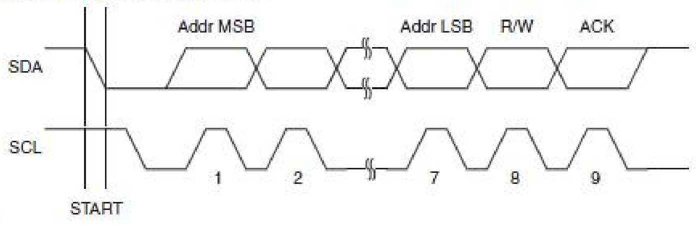
All address packets transmitted on the TWI bus are 9 bits long, consisting of 7 address bits, one READ/WRITE control bit and an acknowledge bit. If the READ/WRITE bit is set, a read operation is to be performed, otherwise a write operation should be performed. When a Slave recognizes that it is being addressed, it should acknowledge by pulling SDA low in the ninth SCL (ACK) cycle. If the addressed Slave is busy, or for some other reason can not service the Master's request, the SDA line should be left high in the ACK clock cycle. The Master can then transmit a STOP condition, or a REPEATED START condition to initiate a new transmission. An address packet consisting of a slave address and a READ or a WRITE bit is called SLA+R or SLA+W, respectively.

The MSB of the address byte is transmitted first. Slave addresses can freely be allocated by the designer, but the address 0000 000 is reserved for a general call.

When a general call is issued, all slaves should respond by pulling the SDA line low in the ACK cycle. A general call is used when a Master wishes to transmit the same message to several slaves in the system. When the general call address followed by a Write bit is transmitted on the bus, all slaves set up to acknowledge the general call will pull the SDA line low in the ack cycle. The following data packets will then be received by all the slaves that acknowledged the general call. Note that transmitting the general call address followed by a Read bit is meaningless, as this would cause contention if several slaves started transmitting different data.

All addresses of the format 1111 xxx should be reserved for future purposes.

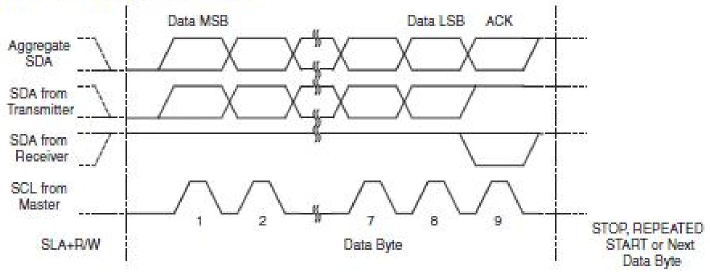
Figure 19-4. Address Packet Format



19.3.4 Data Packet Format

All data packets transmitted on the TWI bus are nine bits long, consisting of one data byte and an acknowledge bit. During a data transfer, the Master generates the clock and the START and STOP conditions, while the Receiver is responsible for acknowledging the reception. An Acknowledge (ACK) is signalled by the Receiver pulling the SDA line low during the ninth SCL cycle. If the Receiver leaves the SDA line high, a NACK is signalled. When the Receiver has received the last byte, or for some reason cannot receive any more bytes, it should inform the Transmitter by sending a NACK after the final byte. The MSB of the data byte is transmitted first.

Figure 19-5. Data Packet Format

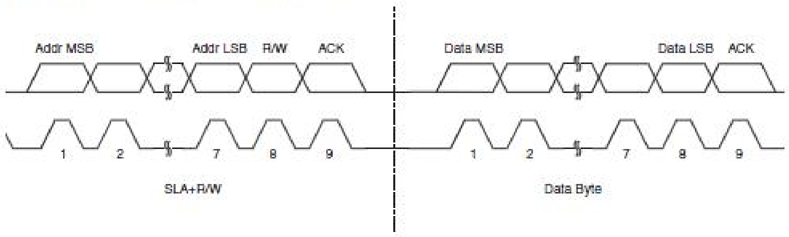


19.3.5 Combining Address and Data Packets into a Transmission

A transmission basically consists of a START condition, a SLA+R/W, one or more data packets and a STOP condition. An empty message, consisting of a START followed by a STOP condition, is illegal. Note that the Wired-ANDing of the SCL line can be used to implement handshaking between the Master and the Slave. The Slave can extend the SCL low period by pulling the SCL line low. This is useful if the clock speed set up by the Master is too fast for the Slave, or the Slave needs extra time for processing between the data transmissions. The Slave extending the SCL low period will not affect the SCL high period, which is determined by the Master. As a consequence, the Slave can reduce the TWI data transfer speed by prolonging the SCL duty cycle.

Figure 19-6 on page 213 shows a typical data transmission. Note that several data bytes can be transmitted between the SLA+R/W and the STOP condition, depending on the software protocol implemented by the application software.

Figure 19-6. Typical Data Transmission



19.4 Multi-master Bus Systems, Arbitration and Synchronization

The TWI protocol allows bus systems with several masters. Special concerns have been taken in order to ensure that transmissions will proceed as normal, even if two or more masters initiate a transmission at the same time. Two problems arise in multi-master systems:

- An algorithm must be implemented allowing only one of the masters to complete the transmission. All other masters should cease transmission when they discover that they have lost the selection process. This selection process is called arbitration. When a contending master discovers that it has lost the arbitration process, it should immediately switch to Slave mode to check whether it is being addressed by the winning master. The fact that multiple masters have started transmission at the same time should not be detectable to the slaves, i.e. the data being transferred on the bus must not be corrupted.
- Different masters may use different SCL frequencies. A scheme must be devised to synchronize the serial clocks from all masters, in order to let the transmission proceed in a lockstep fashion. This will facilitate the arbitration process.

The wired-ANDing of the bus lines is used to solve both these problems. The serial clocks from all masters will be wired-ANDed, yielding a combined clock with a high period equal to the one from the Master with the shortest high period. The low period of the combined clock is equal to the low period of the Master with the longest low period. Note that all masters listen to the SCL line, effectively starting to count their SCL high and low time-out periods when the combined SCL line goes high or low, respectively.

Note that arbitration is not allowed between:

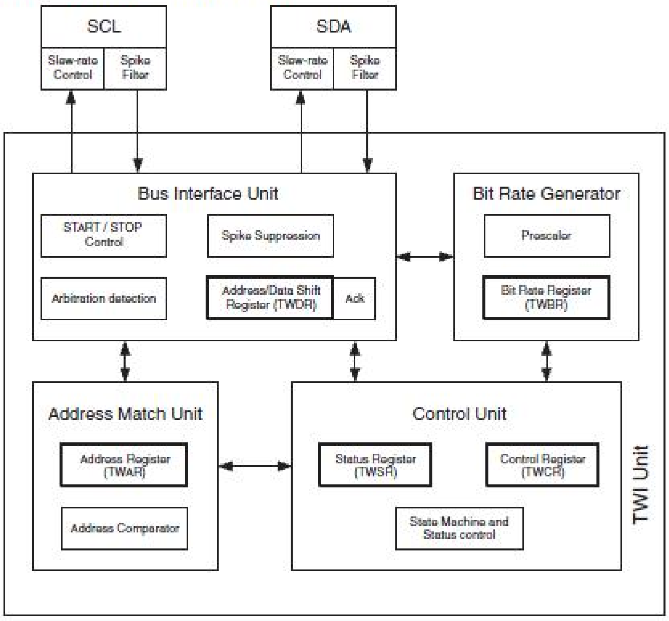
- A REPEATED START condition and a data bit.
- A STOP condition and a data bit.
- A REPEATED START and a STOP condition.

It is the user software's responsibility to ensure that these illegal arbitration conditions never occur. This implies that in multi-master systems, all data transfers must use the same composition of SLA+R/W and data packets. In other words: All transmissions must contain the same number of data packets, otherwise the result of the arbitration is undefined.

19.5 Overview of the TWI Module

The TWI module is comprised of several submodules, as shown in Figure 19-9. All registers drawn in a thick line are accessible through the AVR data bus.

Figure 19-9. Overview of the TWI Module



19.5.1 SCL and SDA Pins

These pins interface the AVR TWI with the rest of the MCU system. The output drivers contain a slew-rate limiter in order to conform to the TWI specification. The input stages contain a spike suppression unit removing spikes shorter than 50 ns. Note that the internal pull-ups in the AVR pads can be enabled by setting the PORT bits corresponding to the SCL and SDA pins, as explained in the I/O Port section. The internal pull-ups can in some systems eliminate the need for external ones.

19.5.2 Bit Rate Generator Unit

This unit controls the period of SCL when operating in a Master mode. The SCL period is controlled by settings in the TWI Bit Rate Register (TWBR) and the Prescaler bits in the TWI Status Register (TWSR). Slave operation does not depend on Bit Rate or Prescaler settings, but the CPU clock frequency in the Slave must be at least 16 times higher than the SCL frequency. Note that slaves may prolong the SCL low period, thereby reducing the average TWI bus clock period. The SCL frequency is generated according to the following equation:

$$\text{SCL frequency} = \frac{\text{CPU Clock frequency}}{16 + 2(\text{TWBR}) \cdot 4^{TWPS}}$$

- TWBR = Value of the TWI Bit Rate Register.
- TWPS = Value of the prescaler bits in the TWI Status Register.

Note: Pull-up resistor values should be selected according to the SCL frequency and the capacitive bus line load. See 2-wire Serial Bus Requirements in Table 26-7 on page 334 for value of pull-up resistor.

19.5.3 Bus Interface Unit

This unit contains the Data and Address Shift Register (TWDR), a START/STOP Controller and Arbitration detection hardware. The TWDR contains the address or data bytes to be transmitted, or the address or data bytes received. In addition to the 8-bit TWDR, the Bus Interface Unit also contains a register containing the (N)ACK bit to be transmitted or received. This (N)ACK Register is not directly accessible by the application software. However, when receiving, it can be set or cleared by manipulating the TWI Control Register (TWCR). When in Transmitter mode, the value of the received (N)ACK bit can be determined by the value in the TWSR.

The START/STOP Controller is responsible for generation and detection of START, REPEATED START, and STOP conditions. The START/STOP controller is able to detect START and STOP conditions even when the AVR MCU is in one of the sleep modes, enabling the MCU to wake up if addressed by a Master.

If the TWI has initiated a transmission as Master, the Arbitration Detection hardware continuously monitors the transmission trying to determine if arbitration is in process. If the TWI has lost an arbitration, the Control Unit is informed. Correct action can then be taken and appropriate status codes generated.

19.5.4 Address Match Unit

The Address Match unit checks if received address bytes match the seven-bit address in the TWI Address Register (TWAR). If the TWI General Call Recognition Enable (TWGCE) bit in the TWAR is written to one, all incoming address bits will also be compared against the General Call address. Upon an address match, the Control Unit is informed, allowing correct action to be taken. The TWI may or may not acknowledge its address, depending on settings in the TWCR. The Address Match unit is able to compare addresses even when the AVR MCU is in sleep mode, enabling the MCU to wake up if addressed by a Master. If another interrupt (e.g., INT0) occurs during TWI Power-down address match and wakes up the CPU, the TWI aborts operation and return to it's idle state. If this cause any problems, ensure that TWI Address Match is the only enabled interrupt when entering Power-down.

19.5.5 Control Unit

The Control unit monitors the TWI bus and generates responses corresponding to settings in the TWI Control Register (TWCR). When an event requiring the attention of the application occurs on the TWI bus, the TWI Interrupt Flag (TWINT) is asserted. In the next clock cycle, the TWI Status Register (TWSR) is updated with a status code identifying the event. The TWSR only contains relevant status information when the TWI Interrupt Flag is asserted. At all other times, the TWSR contains a special status code indicating that no relevant status information is available. As long as the TWINT Flag is set, the SCL line is held low. This allows the application software to complete its tasks before allowing the TWI transmission to continue.

The TWINT Flag is set in the following situations:

- After the TWI has transmitted a START/REPEATED START condition.
- After the TWI has transmitted SLA+R/W.
- After the TWI has transmitted an address byte.
- After the TWI has lost arbitration.
- After the TWI has been addressed by own slave address or general call.
- After the TWI has received a data byte.
- After a STOP or REPEATED START has been received while still addressed as a Slave.
- When a bus error has occurred due to an illegal START or STOP condition.

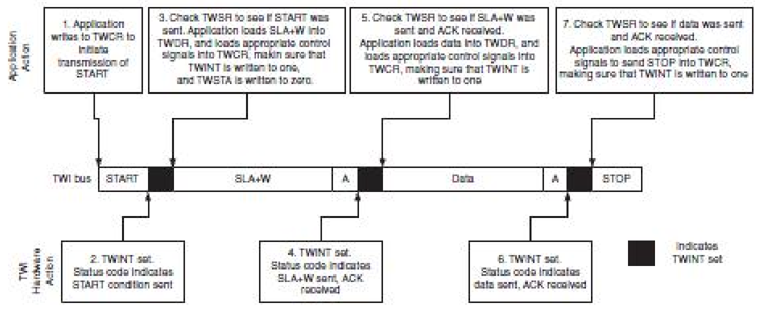
19.6 Using the TWI

The AVR TWI is byte-oriented and interrupt based. Interrupts are issued after all bus events, like reception of a byte or transmission of a START condition. Because the TWI is interrupt-based, the application software is free to carry on other operations during a TWI byte transfer. Note that the TWI Interrupt Enable (TWIE) bit in TWCR together with the Global Interrupt Enable bit in SREG allow the application to decide whether or not assertion of the TWINT Flag should generate an interrupt request. If the TWIE bit is cleared, the application must poll the TWINT Flag in order to detect actions on the TWI bus.

When the TWINT Flag is asserted, the TWI has finished an operation and awaits application response. In this case, the TWI Status Register (TWSR) contains a value indicating the current state of the TWI bus. The application software can then decide how the TWI should behave in the next TWI bus cycle by manipulating the TWCR and TWDR Registers.

Figure 19-10 is a simple example of how the application can interface to the TWI hardware. In this example, a Master wishes to transmit a single data byte to a Slave. This description is quite abstract, a more detailed explanation follows later in this section. A simple code example implementing the desired behavior is also presented.

Figure 19-10. Interfacing the Application to the TWI in a Typical Transmission


Application Action
1. Application writes to TWCR to initiate transmission of START
3. Check TWSR to see if START was sent. Application loads SLA+W into TWDR, and loads appropriate control signals into TWCR, makin sure that TWINT is written to one, and TWSTA is written to zero.
5. Check TWSR to see if SLA+W was sent and ACK received. Application loads data into TWDR, and loads appropriate control signals into TWCR, making sure that TWINT is written to one
7. Check TWSR to see if data was sent and ACK received. Application loads appropriate control signals to send STOP into TWCR, making sure that TWINT is written to one
TWI bus
START
SLA+W
A
Data
A
STOP
TWI Hardware Action
2. TWINT set. Status code indicates START condition sent
4. TWINT set. Status code indicates SLA+W sent, ACK received
6. TWINT set. Status code indicates data sent, ACK received
Indicates TWINT set

1. The first step in a TWI transmission is to transmit a START condition. This is done by writing a specific value into TWCR, instructing the TWI hardware to transmit a START condition. Which value to write is described later on. However, it is important that the TWINT bit is set in the value written. Writing a one to TWINT clears the flag. The TWI will not start any operation as long as the TWINT bit in TWCR is set. Immediately after the application has cleared TWINT, the TWI will initiate transmission of the START condition.
2. When the START condition has been transmitted, the TWINT Flag in TWCR is set, and TWSR is updated with a status code indicating that the START condition has successfully been sent.
3. The application software should now examine the value of TWSR, to make sure that the START condition was successfully transmitted. If TWSR indicates otherwise, the application software might take some special action, like calling an error routine. Assuming that the status code is as expected, the application must load SLA+W into TWDR. Remember that TWDR is used both for address and data. After TWDR has been loaded with the desired SLA+W, a specific value must be written to TWCR, instructing the TWI hardware to transmit the SLA+W present in TWDR. Which value to write is described later on. However, it is important that the TWINT bit is set in the value written. Writing a one to TWINT clears the flag. The TWI will not start any operation as long as the TWINT bit in TWCR is set. Immediately after the application has cleared TWINT, the TWI will initiate transmission of the address packet.
4. When the address packet has been transmitted, the TWINT Flag in TWCR is set, and TWSR is updated with a status code indicating that the address packet has successfully been sent. The status code will also reflect whether a Slave acknowledged the packet or not.

5. The application software should now examine the value of TWSR, to make sure that the address packet was successfully transmitted, and that the value of the ACK bit was as expected. If TWSR indicates otherwise, the application software might take some special action, like calling an error routine. Assuming that the status code is as expected, the application must load a data packet into TWDR. Subsequently, a specific value must be written to TWCR, instructing the TWI hardware to transmit the data packet present in TWDR. Which value to write is described later on. However, it is important that the TWINT bit is set in the value written. Writing a one to TWINT clears the flag. The TWI will not start any operation as long as the TWINT bit in TWCR is set. Immediately after the application has cleared TWINT, the TWI will initiate transmission of the data packet.
6. When the data packet has been transmitted, the TWINT Flag in TWCR is set, and TWSR is updated with a status code indicating that the data packet has successfully been sent. The status code will also reflect whether a Slave acknowledged the packet or not.
7. The application software should now examine the value of TWSR, to make sure that the data packet was successfully transmitted, and that the value of the ACK bit was as expected. If TWSR indicates otherwise, the application software might take some special action, like calling an error routine. Assuming that the status code is as expected, the application must write a specific value to TWCR, instructing the TWI hardware to transmit a STOP condition. Which value to write is described later on. However, it is important that the TWINT bit is set in the value written. Writing a one to TWINT clears the flag. The TWI will not start any operation as long as the TWINT bit in TWCR is set. Immediately after the application has cleared TWINT, the TWI will initiate transmission of the STOP condition. Note that TWINT is NOT set after a STOP condition has been sent.

Even though this example is simple, it shows the principles involved in all TWI transmissions. These can be summarized as follows:

- When the TWI has finished an operation and expects application response, the TWINT Flag is set. The SCL line is pulled low until TWINT is cleared.
- When the TWINT Flag is set, the user must update all TWI Registers with the value relevant for the next TWI bus cycle. As an example, TWDR must be loaded with the value to be transmitted in the next bus cycle.
- After all TWI Register updates and other pending application software tasks have been completed, TWCR is written. When writing TWCR, the TWINT bit should be set. Writing a one to TWINT clears the flag. The TWI will then commence executing whatever operation was specified by the TWCR setting.

In the following an assembly and C implementation of the example is given. Note that the code below assumes that several definitions have been made, for example by using include-files.

	Assembly Code Example	C Example	Comments

1	`ldi r16, (1<<TWINT)|(1<<TWSTA)|`
	`(1<<TWEN)`
	`out TWCR, r16`
		`TWCR = (1<<TWINT)|(1<<TWSTA)|`
		`(1<<TWEN)`
			Send START condition

2	`wait1:`
	`in r16,TWCR`
	`sbrs r16,TWINT`
	`rjmp wait1`
		`while (!(TWCR & (1<<TWINT)))`
		`;`
			Wait for TWINT Flag set. This indicates that the START condition has been transmitted

3	`in r16,TWSR`
	`andi r16, 0xF8`
	`cpi r16, START`
	`brne ERROR`
		`if ((TWSR & 0xF8) != START)`
		`ERROR();`
			Check value of TWI Status Register. Mask prescaler bits. If status different from START go to ERROR

	`ldi r16, SLA_W`
	`out TWDR, r16`
	`ldi r16, (1<<TWINT) | (1<<TWEN)`
	`out TWCR, r16`
		`TWDR = SLA_W;`
		`TWCR = (1<<TWINT) | (1<<TWEN);`
			Load SLA_W into TWDR Register. Clear TWINT bit in TWCR to start transmission of address

4	`wait2:`
	`in r16,TWCR`
	`sbrs r16,TWINT`
	`rjmp wait2`
		`while (!(TWCR & (1<<TWINT)))`
		`;`
			Wait for TWINT Flag set. This indicates that the SLA+W has been transmitted, and ACK/NACK has been received.

5	`in r16,TWSR`
	`andi r16, 0xF8`
	`cpi r16, MT_SLA_ACK`
	`brne ERROR`
		`if ((TWSR & 0xF8) !=`
		`MT_SLA_ACK)`
		`ERROR();`
			Check value of TWI Status Register. Mask prescaler bits. If status different from MT_SLA_ACK go to ERROR

	`ldi r16, DATA`
	`out TWDR, r16`
	`ldi r16, (1<<TWINT) | (1<<TWEN)`
	`out TWCR, r16`
		`TWDR = DATA;`
		`TWCR = (1<<TWINT) | (1<<TWEN);`
			Load DATA into TWDR Register. Clear TWINT bit in TWCR to start transmission of data

6	`wait3:`
	`in r16,TWCR`
	`sbrs r16,TWINT`
	`rjmp wait3`
		`while (!(TWCR & (1<<TWINT)))`
		`;`
			Wait for TWINT Flag set. This indicates that the DATA has been transmitted, and ACK/NACK has been received.

7	`in r16,TWSR`
	`andi r16, 0xF8`
	`cpi r16, MT_DATA_ACK`
	`brne ERROR`
		`if ((TWSR & 0xF8) !=`
		`MT_DATA_ACK)`
		`ERROR();`
			Check value of TWI Status Register. Mask prescaler bits. If status different from MT_DATA_ACK go to ERROR

	`ldi r16, (1<<TWINT)|(1<<TWEN)|`
	`(1<<TWSTO)`
	`out TWCR, r16`
		`TWCR = (1<<TWINT)|(1<<TWEN)|`
		`(1<<TWSTO);`
			Transmit STOP condition

19.7 Transmission Modes

The TWI can operate in one of four major modes. These are named Master Transmitter (MT), Master Receiver (MR), Slave Transmitter (ST) and Slave Receiver (SR). Several of these modes can be used in the same application. As an example, the TWI can use MT mode to write data into a TWI EEPROM, MR mode to read the data back from the EEPROM. If other masters are present in the system, some of these might transmit data to the TWI, and then SR mode would be used. It is the application software that decides which modes are legal.

The following sections describe each of these modes. Possible status codes are described along with figures detailing data transmission in each of the modes. These figures contain the following abbreviations:

S: START condition

Rs: REPEATED START condition

R: Read bit (high level at SDA)

W: Write bit (low level at SDA)

A: Acknowledge bit (low level at SDA)

$\overline{A}$: Not acknowledge bit (high level at SDA)

Data: 8-bit data byte

P: STOP condition

SLA: Slave Address

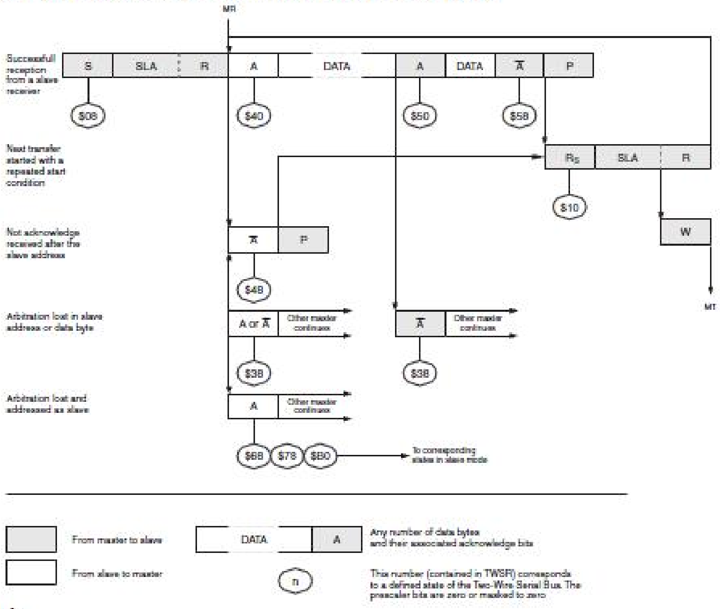
In Figure 19-12 on page 224 to Figure 19-18 on page 233, circles are used to indicate that the TWINT Flag is set. The numbers in the circles show the status code held in TWSR, with the prescaler bits masked to zero. At these points, actions must be taken by the application to continue or complete the TWI transfer. The TWI transfer is suspended until the TWINT Flag is cleared by software.

When the TWINT Flag is set, the status code in TWSR is used to determine the appropriate software action. For each status code, the required software action and details of the following serial transfer are given in Table 19-2 on page 223 to Table 19-5 on page 232. Note that the prescaler bits are masked to zero in these tables.

19.7.1 Master Transmitter Mode

In the Master Transmitter mode, a number of data bytes are transmitted to a Slave Receiver (see Figure 19-11 on page 222). In order to enter a Master mode, a START condition must be transmitted. The format of the following address packet determines whether Master Transmitter or Master Receiver mode is to be entered. If SLA+W is transmitted, MT mode is entered, if SLA+R is transmitted, MR mode is entered. All the status codes mentioned in this section assume that the prescaler bits are zero or are masked to zero.

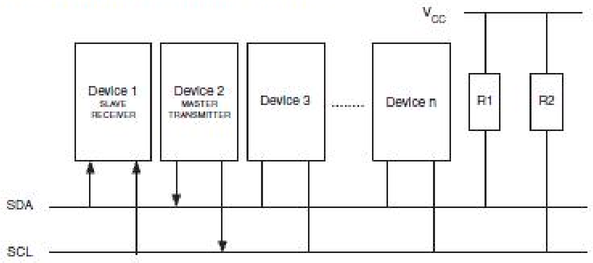
Figure 19-14. Formats and States in the Master Receiver Mode


MR
Successfull reception from a slave receiver
S
SLA
R
A
DATA
A
DATA
$\overline{A}$
P
$08
$40
$50
$58
Next transfer started with a repeated start condition
R_S
SLA
R
$10
W
MT
Not acknowledge received after the slave address
$\overline{A}$
P
$48
Arbitration lost in slave address or data byte
A or $\overline{A}$
Other master continues
$\overline{A}$
Other master continues
$38
$38
Arbitration lost and addressed as slave
A
Other master continues
$68
$78
$B0
To corresponding states in slave mode
From master to slave
From slave to master
DATA
A
Any number of data bytes and their associated acknowledge bits
n
This number (contained in TWSR) corresponds to a defined state of the Two-Wire Serial Bus. The prescaler bits are zero or masked to zero

19.7.3 Slave Receiver Mode

In the Slave Receiver mode, a number of data bytes are received from a Master Transmitter (see Figure 19-15). All the status codes mentioned in this section assume that the prescaler bits are zero or are masked to zero.

Figure 19-15. Data transfer in Slave Receiver mode



To initiate the Slave Receiver mode, TWAR and TWCR must be initialized as follows:

TWAR	TWA6	TWA5	TWA4	TWA3	TWA2	TWA1	TWA0	TWGCE
value	Device's Own Slave Address							

The upper 7 bits are the address to which the 2-wire Serial Interface will respond when addressed by a Master. If the LSB is set, the TWI will respond to the general call address (0x00), otherwise it will ignore the general call address.

TWCR	TWINT	TWEA	TWSTA	TWSTO	TWWC	TWEN	–	TWIE
value	0	1	0	0	0	1	0	X

TWEN must be written to one to enable the TWI. The TWEA bit must be written to one to enable the acknowledgement of the device's own slave address or the general call address. TWSTA and TWSTO must be written to zero.

When TWAR and TWCR have been initialized, the TWI waits until it is addressed by its own slave address (or the general call address if enabled) followed by the data direction bit. If the direction bit is "0" (write), the TWI will operate in SR mode, otherwise ST mode is entered. After its own slave address and the write bit have been received, the TWINT Flag is set and a valid status code can be read from TWSR. The status code is used to determine the appropriate software action. The appropriate action to be taken for each status code is detailed in Table 19-4 on page 229. The Slave Receiver mode may also be entered if arbitration is lost while the TWI is in the Master mode (see states 0x68 and 0x78).

If the TWEA bit is reset during a transfer, the TWI will return a "Not Acknowledge" ("1") to SDA after the next received data byte. This can be used to indicate that the Slave is not able to receive any more bytes. While TWEA is zero, the TWI does not acknowledge its own slave address. However, the 2-wire Serial Bus is still monitored and address recognition may resume at any time by setting TWEA. This implies that the TWEA bit may be used to temporarily isolate the TWI from the 2-wire Serial Bus.

In all sleep modes other than Idle mode, the clock system to the TWI is turned off. If the TWEA bit is set, the interface can still acknowledge its own slave address or the general call address by using the 2-wire Serial Bus clock as a clock source. The part will then wake up from sleep and the TWI will hold the SCL clock low during the wake up and until the TWINT Flag is cleared (by writing it to one). Further data reception will be carried out as normal, with the AVR clocks running as normal. Observe that if the AVR is set up with a long start-up time, the SCL line may be held low for a long time, blocking other data transmissions.

Note that the 2-wire Serial Interface Data Register – TWDR does not reflect the last byte present on the bus when waking up from these Sleep modes.

Table 19-4. Status Codes for Slave Receiver Mode

Status Code (TWSR) Prescaler Bits are 0	Status of the 2-wire Serial Bus and 2-wire Serial Interface Hardware	Application Software Response					Next Action Taken by TWI Hardware
			To TWCR				
		To/from TWDR	STA	STO	TWINT	TWEA	
0x60	Own SLA+W has been received; ACK has been returned	No TWDR action or	X	0	1	0	Data byte will be received and NOT ACK will be returned
		No TWDR action	X	0	1	1	Data byte will be received and ACK will be returned
0x68	Arbitration lost in SLA+R/W as Master; own SLA+W has been received; ACK has been returned	No TWDR action or	X	0	1	0	Data byte will be received and NOT ACK will be returned
		No TWDR action	X	0	1	1	Data byte will be received and ACK will be returned
0x70	General call address has been received; ACK has been returned	No TWDR action or	X	0	1	0	Data byte will be received and NOT ACK will be returned
		No TWDR action	X	0	1	1	Data byte will be received and ACK will be returned
0x78	Arbitration lost in SLA+R/W as Master; General call address has been received; ACK has been returned	No TWDR action or	X	0	1	0	Data byte will be received and NOT ACK will be returned
		No TWDR action	X	0	1	1	Data byte will be received and ACK will be returned
0x80	Previously addressed with own SLA+W; data has been received; ACK has been returned	Read data byte or	X	0	1	0	Data byte will be received and NOT ACK will be returned
		Read data byte	X	0	1	1	Data byte will be received and ACK will be returned
0x88	Previously addressed with own SLA+W; data has been received; NOT ACK has been returned	Read data byte or	0	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA
		Read data byte or	0	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"
		Read data byte or	1	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA; a START condition will be transmitted when the bus becomes free
		Read data byte	1	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"; a START condition will be transmitted when the bus becomes free
0x90	Previously addressed with general call; data has been re- ceived; ACK has been returned	Read data byte or	X	0	1	0	Data byte will be received and NOT ACK will be returned
		Read data byte	X	0	1	1	Data byte will be received and ACK will be returned
0x98	Previously addressed with general call; data has been received; NOT ACK has been returned	Read data byte or	0	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA
		Read data byte or	0	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"
		Read data byte or	1	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA; a START condition will be transmitted when the bus becomes free
		Read data byte	1	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"; a START condition will be transmitted when the bus becomes free
0xA0	A STOP condition or repeated START condition has been received while still addressed as Slave	No action	0	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA
			0	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"
			1	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA; a START condition will be transmitted when the bus becomes free
			1	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"; a START condition will be transmitted when the bus becomes free

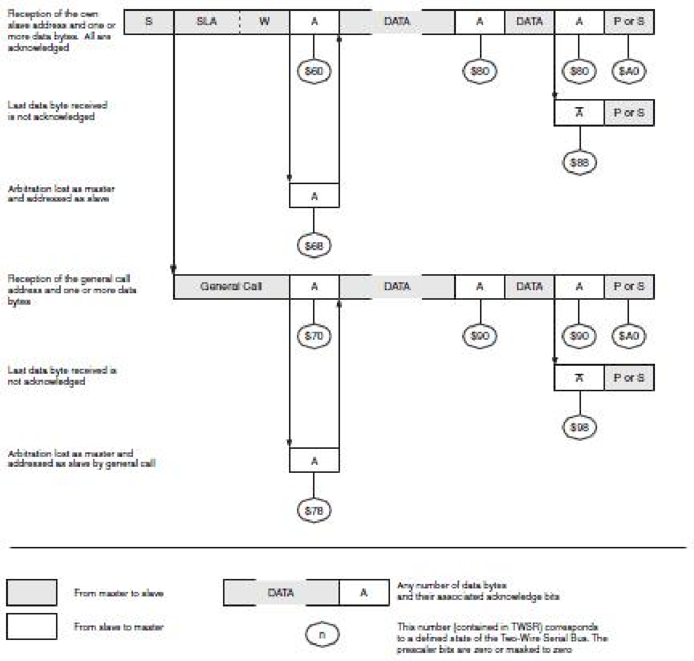
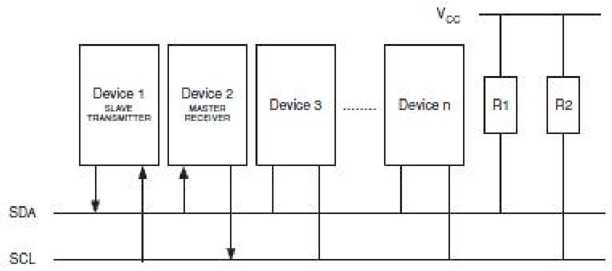

Reception of the own slave address and one or more data bytes. All are acknowledged
S
SLA
W
A
DATA
A
DATA
A
P or S
$60
$80
$80
$A0
Last data byte received is not acknowledged
$\overline{A}$
P or S
$88
Arbitration lost as master and addressed as slave
A
$68
Reception of the general call address and one or more data bytes
General Call
A
DATA
A
DATA
A
P or S
$70
$90
$90
$A0
Last data byte received is not acknowledged
$\overline{A}$
P or S
$98
Arbitration lost as master and addressed as slave by general call
A
$78
From master to slave
From slave to master
DATA
A
Any number of data bytes and their associated acknowledge bits
n
This number (contained in TWSR) corresponds to a defined state of the Two-Wire Serial Bus. The prescaler bits are zero or masked to zero

Figure 19-16. Formats and States in the Slave Receiver Mode

19.7.4 Slave Transmitter Mode

In the Slave Transmitter mode, a number of data bytes are transmitted to a Master Receiver (see Figure 19-17). All the status codes mentioned in this section assume that the prescaler bits are zero or are masked to zero.

Figure 19-17. Data Transfer in Slave Transmitter Mode



To initiate the Slave Transmitter mode, TWAR and TWCR must be initialized as follows:

TWAR	TWA6	TWA5	TWA4	TWA3	TWA2	TWA1	TWA0	TWGCE
value	Device's Own Slave Address							

The upper seven bits are the address to which the 2-wire Serial Interface will respond when addressed by a Master. If the LSB is set, the TWI will respond to the general call address (0x00), otherwise it will ignore the general call address.

TWCR	TWINT	TWEA	TWSTA	TWSTO	TWWC	TWEN	–	TWIE
value	0	1	0	0	0	1	0	X

TWEN must be written to one to enable the TWI. The TWEA bit must be written to one to enable the acknowledgement of the device's own slave address or the general call address. TWSTA and TWSTO must be written to zero.

When TWAR and TWCR have been initialized, the TWI waits until it is addressed by its own slave address (or the general call address if enabled) followed by the data direction bit. If the direction bit is "1" (read), the TWI will operate in ST mode, otherwise SR mode is entered. After its own slave address and the write bit have been received, the TWINT Flag is set and a valid status code can be read from TWSR. The status code is used to determine the appropriate software action. The appropriate action to be taken for each status code is detailed in Table 19-5 on page 232. The Slave Transmitter mode may also be entered if arbitration is lost while the TWI is in the Master mode (see state 0xB0).

If the TWEA bit is written to zero during a transfer, the TWI will transmit the last byte of the transfer. State 0xC0 or state 0xC8 will be entered, depending on whether the Master Receiver transmits a NACK or ACK after the final byte. The TWI is switched to the not addressed Slave mode, and will ignore the Master if it continues the transfer. Thus the Master Receiver receives all "1" as serial data. State 0xC8 is entered if the Master demands additional data bytes (by transmitting ACK), even though the Slave has transmitted the last byte (TWEA zero and expecting NACK from the Master).

While TWEA is zero, the TWI does not respond to its own slave address. However, the 2-wire Serial Bus is still monitored and address recognition may resume at any time by setting TWEA. This implies that the TWEA bit may be used to temporarily isolate the TWI from the 2-wire Serial Bus.

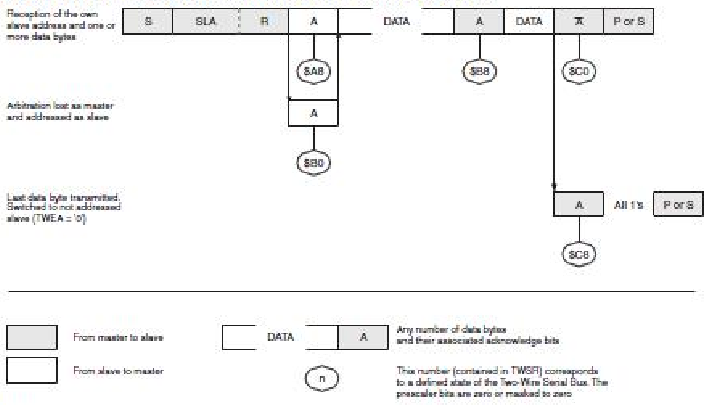
In all sleep modes other than Idle mode, the clock system to the TWI is turned off. If the TWEA bit is set, the interface can still acknowledge its own slave address or the general call address by using the 2-wire Serial Bus clock as a clock source. The part will then wake up from sleep and the TWI will hold the SCL clock will low during the wake up and until the TWINT Flag is cleared (by writing it to one). Further data transmission will be carried out as normal, with the AVR clocks running as normal. Observe that if the AVR is set up with a long start-up time, the SCL line may be held low for a long time, blocking other data transmissions.

Note that the 2-wire Serial Interface Data Register – TWDR does not reflect the last byte present on the bus when waking up from these sleep modes.

Table 19-5. Status Codes for Slave Transmitter Mode

Status Code (TWSR) Prescaler Bits are 0	Status of the 2-wire Serial Bus and 2-wire Serial Interface Hardware	Application Software Response					Next Action Taken by TWI Hardware
		To/from TWDR	To TWCR				
			STA	STO	TWINT	TWEA	
0xA8	Own SLA+R has been received; ACK has been returned	Load data byte or	X	0	1	0	Last data byte will be transmitted and NOT ACK should be received
		Load data byte	X	0	1	1	Data byte will be transmitted and ACK should be received
0xB0	Arbitration lost in SLA+R/W as Master; own SLA+R has been received; ACK has been returned	Load data byte or	X	0	1	0	Last data byte will be transmitted and NOT ACK should be received
		Load data byte	X	0	1	1	Data byte will be transmitted and ACK should be received
0xB8	Data byte in TWDR has been transmitted; ACK has been received	Load data byte or	X	0	1	0	Last data byte will be transmitted and NOT ACK should be received
		Load data byte	X	0	1	1	Data byte will be transmitted and ACK should be received
0xC0	Data byte in TWDR has been transmitted; NOT ACK has been received	No TWDR action or	0	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA
		No TWDR action or	0	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"
		No TWDR action or	1	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA; a START condition will be transmitted when the bus becomes free
		No TWDR action	1	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"; a START condition will be transmitted when the bus becomes free
0xC8	Last data byte in TWDR has been transmitted (TWEA = "0"); ACK has been received	No TWDR action or	0	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA
		No TWDR action or	0	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"
		No TWDR action or	1	0	1	0	Switched to the not addressed Slave mode; no recognition of own SLA or GCA; a START condition will be transmitted when the bus becomes free
		No TWDR action	1	0	1	1	Switched to the not addressed Slave mode; own SLA will be recognized; GCA will be recognized if TWGCE = "1"; a START condition will be transmitted when the bus becomes free

Figure 19-18. Formats and States in the Slave Transmitter Mode


Reception of the own slave address and one or more data bytes
S
SLA
R
A
DATA
A
DATA
$\overline{A}$
P or S
$A8
$B8
$C0
Arbitration lost as master and addressed as slave
A
$B0
Last data byte transmitted. Switched to not addressed slave (TWEA = '0')
A
All 1's
P or S
$C8
From master to slave
From slave to master
DATA
A
Any number of data bytes and their associated acknowledge bits
n
This number (contained in TWSR) corresponds to a defined state of the Two-Wire Serial Bus. The prescaler bits are zero or masked to zero

19.7.5 Miscellaneous States

There are two status codes that do not correspond to a defined TWI state, see Table 19-6.

Status 0xF8 indicates that no relevant information is available because the TWINT Flag is not set. This occurs between other states, and when the TWI is not involved in a serial transfer.

Status 0x00 indicates that a bus error has occurred during a 2-wire Serial Bus transfer. A bus error occurs when a START or STOP condition occurs at an illegal position in the format frame. Examples of such illegal positions are during the serial transfer of an address byte, a data byte, or an acknowledge bit. When a bus error occurs, TWINT is set. To recover from a bus error, the TWSTO Flag must set and TWINT must be cleared by writing a logic one to it. This causes the TWI to enter the not addressed Slave mode and to clear the TWSTO Flag (no other bits in TWCR are affected). The SDA and SCL lines are released, and no STOP condition is transmitted.

Table 19-6. Miscellaneous States

Status Code (TWSR) Prescaler Bits are 0	Status of the 2-wire Serial Bus and 2-wire Serial Interface Hardware	Application Software Response					Next Action Taken by TWI Hardware
		To/from TWDR	To TWCR				
			STA	STO	TWINT	TWEA	
0xF8	No relevant state information available; TWINT = "0"	No TWDR action	No TWCR action				Wait or proceed current transfer
0x00	Bus error due to an illegal START or STOP condition	No TWDR action	0	1	1	X	Only the internal hardware is affected, no STOP condition is sent on the bus. In all cases, the bus is released and TWSTO is cleared.

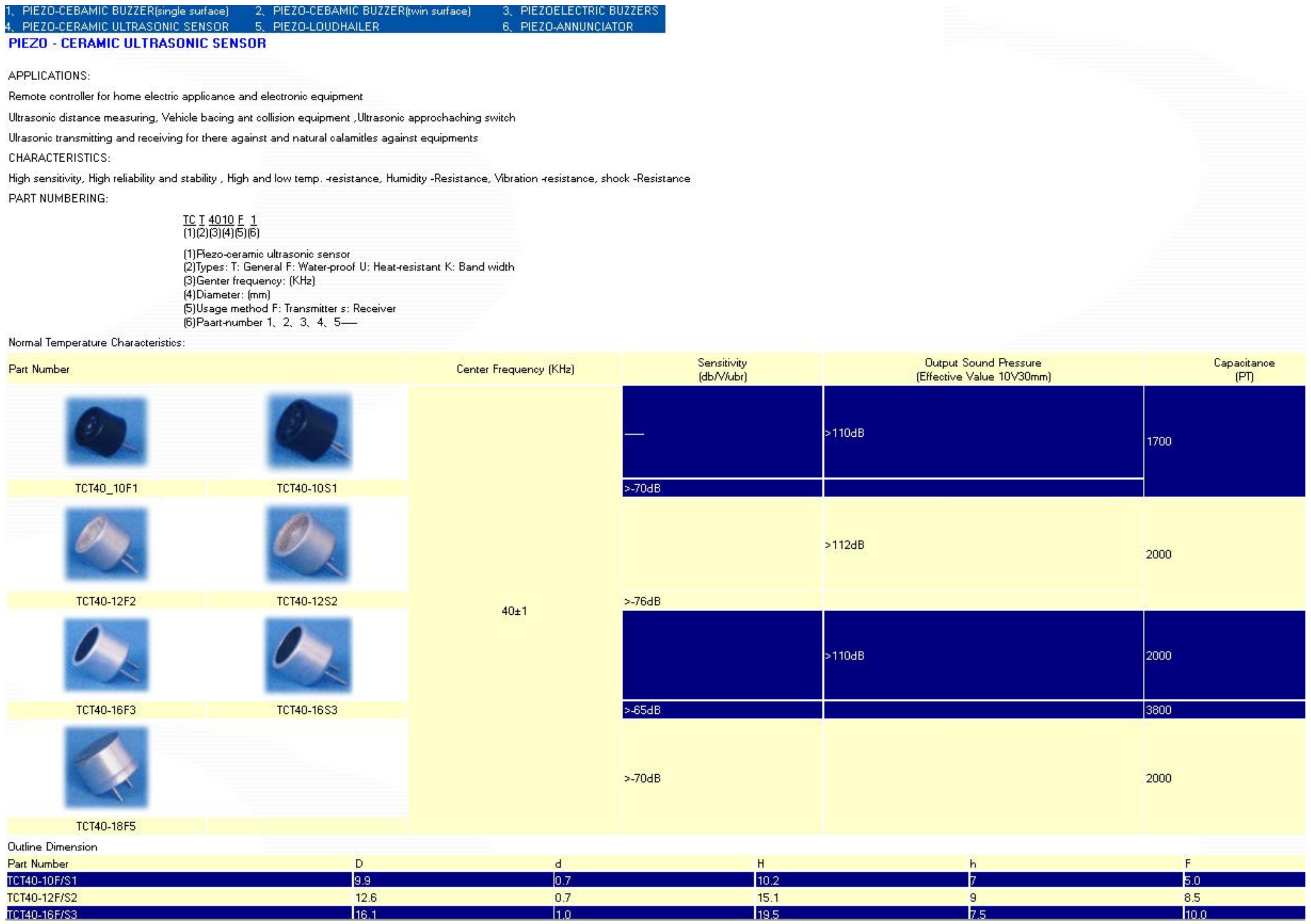
19.7.6 Combining Several TWI Modes

In some cases, several TWI modes must be combined in order to complete the desired action. Consider for example reading data from a serial EEPROM. Typically, such a transfer involves the following steps:

1. The transfer must be initiated.
2. The EEPROM must be instructed what location should be read.
3. The reading must be performed.
4. The transfer must be finished.

Appendix B

B.1 Ultrasonic sensor piezo sender and receiver



1、PIEZO-CEBAMIC BUZZER(single surface) 2、PIEZO-CEBAMIC BUZZER(twin surface) 3、PIEZOELECTRIC BUZZERS
4、PIEZO-CERAMIC ULTRASONIC SENSOR 5、PIEZO-LOUDHAILER 6、PIEZO-ANNUNCIATOR

PIEZO - CERAMIC ULTRASONIC SENSOR

APPLICATIONS:

Remote controller for home electric applicance and electronic equipment

Ultrasonic distance measuring, Vehicle bacing ant collision equipment ,Ultrasonic approchaching switch

Ulrasonic transmitting and receiving for there against and natural calamitles against equipments

CHARACTERISTICS:

High sensitivity, High reliability and stability , High and low temp. -resistance, Humidity -Resistance, Vibration -resistance, shock -Resistance

PART NUMBERING:

TC T 4010 F 1
(1)(2)(3)(4)(5)(6)

(1)Piezo-ceramic ultrasonic sensor
(2)Types: T: General F: Water-proof U: Heat-resistant K: Band width
(3)Genter frequency: (KHz)
(4)Diameter: (mm)
(5)Usage method F: Transmitter s: Receiver
(6)Paart-number 1、2、3、4、5—

Normal Temperature Characteristics:

Part Number	Center Frequency (KHz)	Sensitivity (db/V/ubr)	Output Sound Pressure (Effective Value 10V30mm)	Capacitance (PT)
TCT40_10F1	40±1	—	>110dB	1700
TCT40-10S1		>-70dB		
TCT40-12F2			>112dB	2000
TCT40-12S2		>-76dB		
TCT40-16F3			>110dB	2000
TCT40-16S3		>-65dB		3800
TCT40-18F5		>-70dB		2000

Outline Dimension

Part Number	D	d	H	h	F
TCT40-10F/S1	9.9	0.7	10.2	7	5.0
TCT40-12F/S2	12.6	0.7	15.1	9	8.5
TCT40-16F/S3	16.1	1.0	19.5	7.5	10.0

from http://www.ke-lei.com/ecp4.htm

B.2 Light Sensor Phototransistor

NPN-Silizium-Fototransistor
Silicon NPN Phototransistor

SFH 309
SFH 309 FA

SFH 309

SFH 309 FA

Wesentliche Merkmale	**Features**
• Speziell geeignet für Anwendungen im Bereich von 380 nm bis 1180 nm (SFH 309) und bei 880 nm (SFH 309 FA)	• Especially suitable for applications from 380 nm to 1180 nm (SFH 309) and of 880 nm (SFH 309 FA)
• Hohe Linearität	• High linearity
• 3 mm-Plastikbauform im LED-Gehäuse	• 3 mm LED plastic package
• Gruppiert lieferbar	• Available in groups

Anwendungen
- Lichtschranken für Gleich- und Wechsellichtbetrieb
- Industrieelektronik
- „Messen/Steuern/Regeln“

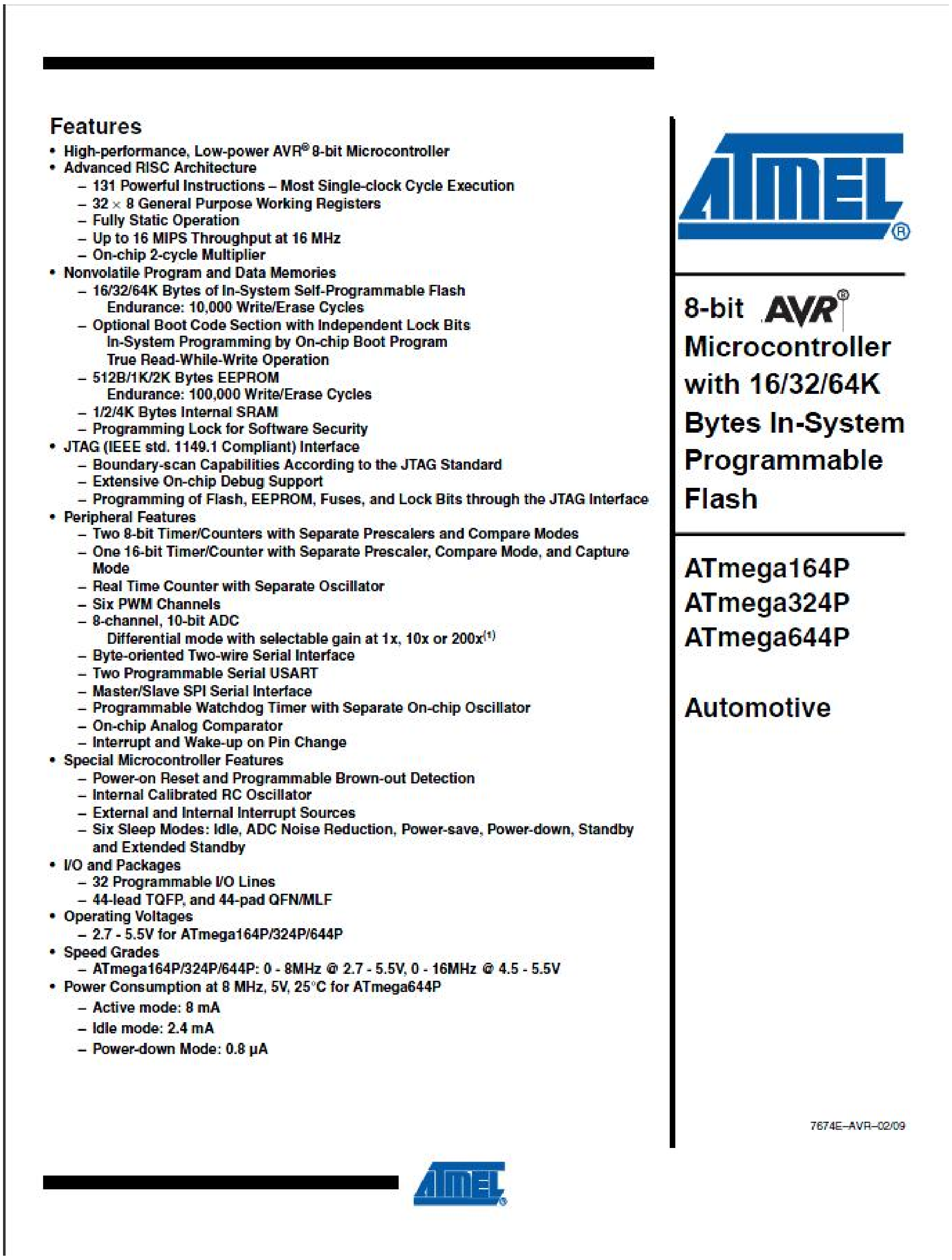
Applications
- Photointerrupters
- Industrial electronics
- For control and drive circuits

Typ Type	Bestellnummer Ordering Code	Typ Type	Bestellnummer Ordering Codes
SFH 309	Q62702-P859	SFH 309 FA	Q62702-P941
SFH 309-3/4	Q62702-P3592	SFH 309 FA-3/4	Q62702-P3590
SFH 309-4	Q62702-P998	SFH 309 FA-4	Q62702-P178
SFH 309-4/5	Q62702-P3593	SFH 309 FA-4/5	Q62702-P3591
SFH 309-5	Q62702-P999	SFH 309 FA-5	Q62702-P180
SFH 309-5/6	Q62702-P3594	SFH 309 FA-5/6	Q62702-P5199

Appendix C

Expansion Board

C.1 ATMega 164P



Features

- High-performance, Low-power AVR® 8-bit Microcontroller
- Advanced RISC Architecture
  - 131 Powerful Instructions – Most Single-clock Cycle Execution
  - 32 × 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 16 MIPS Throughput at 16 MHz
  - On-chip 2-cycle Multiplier
- Nonvolatile Program and Data Memories
  - 16/32/64K Bytes of In-System Self-Programmable Flash
    Endurance: 10,000 Write/Erase Cycles
  - Optional Boot Code Section with Independent Lock Bits
    In-System Programming by On-chip Boot Program
    True Read-While-Write Operation
  - 512B/1K/2K Bytes EEPROM
    Endurance: 100,000 Write/Erase Cycles
  - 1/2/4K Bytes Internal SRAM
  - Programming Lock for Software Security
- JTAG (IEEE std. 1149.1 Compliant) Interface
  - Boundary-scan Capabilities According to the JTAG Standard
  - Extensive On-chip Debug Support
  - Programming of Flash, EEPROM, Fuses, and Lock Bits through the JTAG Interface
- Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescalers and Compare Modes
  - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode
  - Real Time Counter with Separate Oscillator
  - Six PWM Channels
  - 8-channel, 10-bit ADC
    Differential mode with selectable gain at 1x, 10x or 200x[1]
  - Byte-oriented Two-wire Serial Interface
  - Two Programmable Serial USART
  - Master/Slave SPI Serial Interface
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
  - Interrupt and Wake-up on Pin Change
- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated RC Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby and Extended Standby
- I/O and Packages
  - 32 Programmable I/O Lines
  - 44-lead TQFP, and 44-pad QFN/MLF
- Operating Voltages
  - 2.7 - 5.5V for ATmega164P/324P/644P
- Speed Grades
  - ATmega164P/324P/644P: 0 - 8MHz @ 2.7 - 5.5V, 0 - 16MHz @ 4.5 - 5.5V
- Power Consumption at 8 MHz, 5V, 25°C for ATmega644P
  - Active mode: 8 mA
  - Idle mode: 2.4 mA
  - Power-down Mode: 0.8 µA

8-bit AVR® Microcontroller with 16/32/64K Bytes In-System Programmable Flash

ATmega164P
ATmega324P
ATmega644P

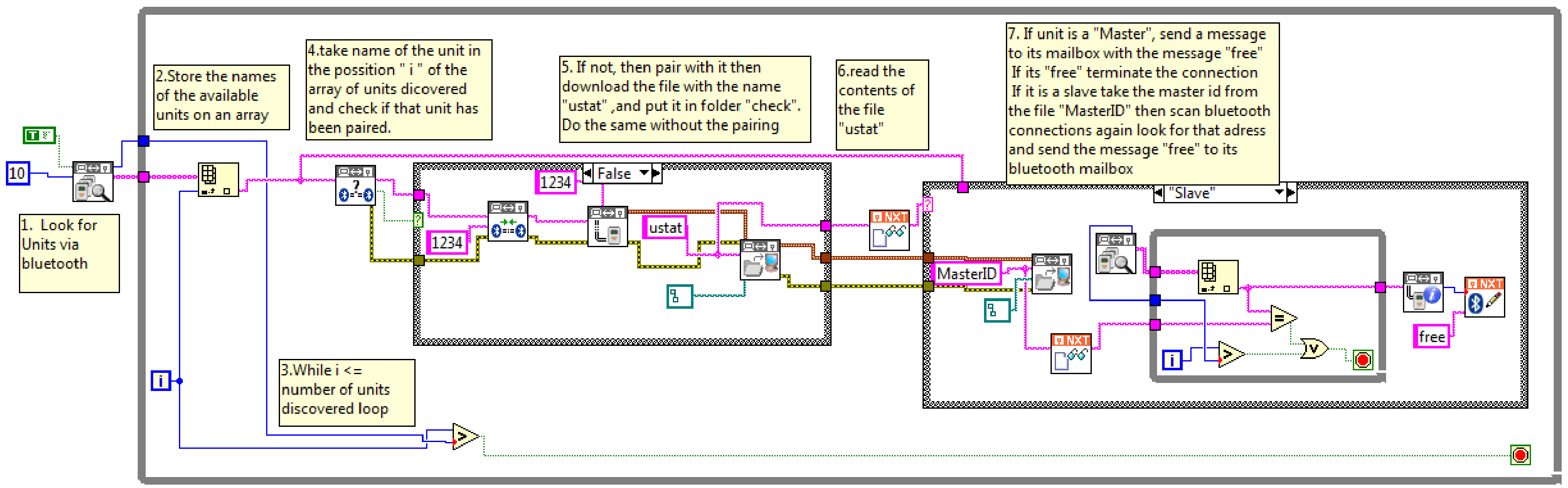
Automotive

7674E–AVR–02/09

Appendix D

LabVIEW Virtual Instruments

E.1 LAF.vi



1. Look for Units via bluetooth

2.Store the names of the available units on an array

3.While i <= number of units discovered loop

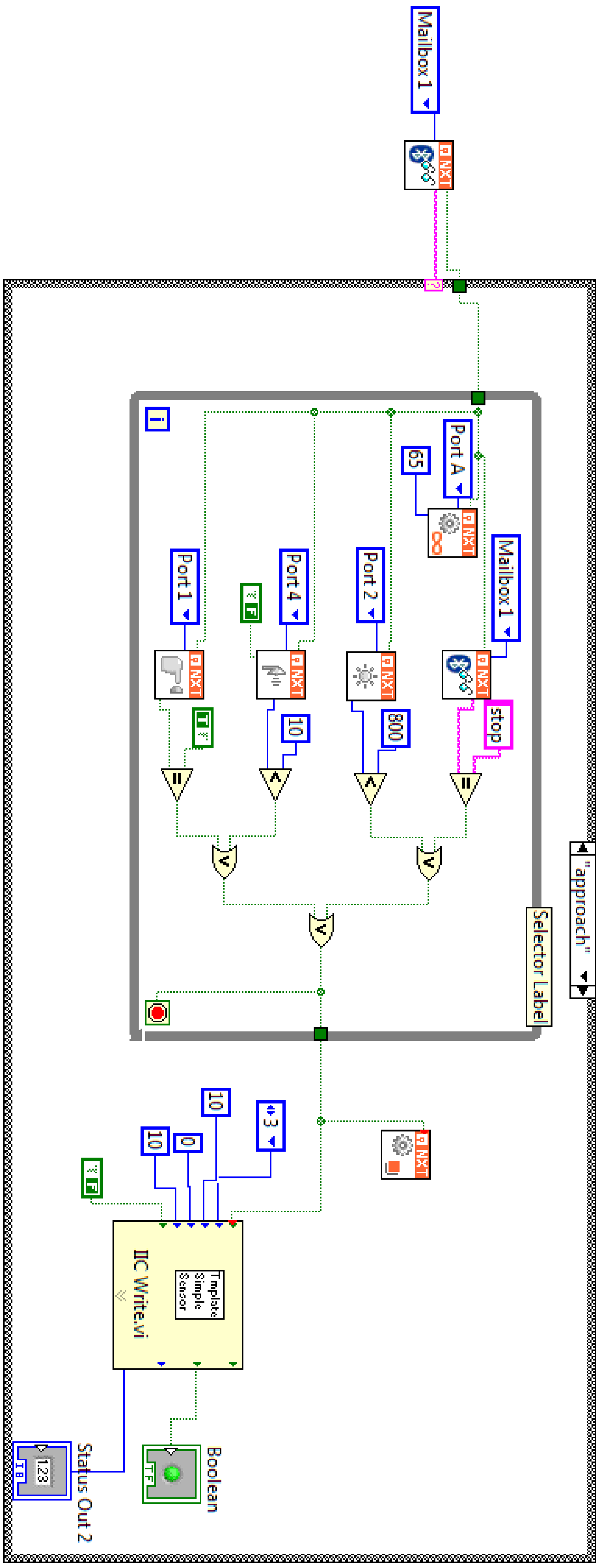
4.take name of the unit in the possition " i " of the array of units discovered and check if that unit has been paired.

5. If not, then pair with it then download the file with the name "ustat" ,and put it in folder "check". Do the same without the pairing

6.read the contents of the file "ustat"

7. If unit is a "Master", send a message to its mailbox with the message "free"
If its "free" terminate the connection
If it is a slave take the master id from the file "MasterID" then scan bluetooth connections again look for that adress and send the message "free" to its bluetooth mailbox

E.2 slave.vi when in approach mode


Mailbox 1
NXT
Port A
65
Mailbox 1
Port 1
Port 4
Port 2
10
800
stop
"approach"
Selector Label
10
0
10
3
IIC Write.vi
Tmplate Simple Sensor
Status Out 2
Boolean