Mechanical Design of New, Hybrid Modular Reconfigurable Robotic System

Ali KILIÇ, Sadettin KAPUCU

***Abstract*—** OMNIMO as a modular reconfigurable robot module which can navigate and perform some simple tasks, for complicated duties, proper robot type can be constructed by multiple homogeneous robot modules. It has five different active degrees of freedom which are four revolute and one prismatic. Mobilities of robot can be used as fixed, free and actuated. Each robot module is equipped with some sort of controllers, actuators, sensing elements, a wireless communication unit, power source and complementary electronic and mechanical components. The robot module is designed to move in three dimensional workspace as a hybrid, homogeneous and autonomous. This paper describes details of the sophisticated mechanical design, manufacturing details and hardware implementation of the OMNIMO.

***Keywords*—**Mechanical Design, Modular Robot, Reconfigurable Robot, Robotic Module

I. Introduction

The concept of modularity in design has long existed in many engineering fields. The main idea behind this approach is to divide a complicated system into small functional modules with high flexibility, dexterity and ease of maintenance. From robotic perspective, unlike the conventional robotic systems, modular reconfigurable robots combine the features and capabilities of multiple robotic modules to achieve the objectives that are beyond the capabilities of a single robot. As it is seen clearly, these robots are more complex than conventional robotic systems in terms of their design and control. For this reason, in last three decades reconfigurable modular robotics has become a new and challenging research area in robotics. In this revolutionary approach, a robot module can navigate and perform some simple tasks, for complicated duties, proper robot type can be constructed by multiple homogeneous or heterogeneous robot modules.

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In order to do that these modules are connected together at specific, predefined, standardized connecting interface. Modular robot elements typically contain a controller, sensing elements, actuation mechanisms, communication systems, complementary mechanical and electronic elements and a control software for performing the desired tasks. Furthermore, mechanical structure of robot can be changed dynamically between two tasks. This feature enables many of the tasks and applications can be made with a single robot module or combination of multi robot modules.

Modular reconfigurable robots can be seen various forms and architectures and also so many potential application areas [1]. The starting point of modular reconfigurable robot concept is end effector and automatic tool changers in NC/CNC machining centers in the 1970's. An electromechanical common connection mechanism exist in order to connect tools to machine center. The concept of a common connection mechanism to an entirely modular robot was introduced by Fukuda with the CEBOT in the 1988 [1]. Here each CEBOT module is 180 x 90 x 50 mm and it has 1.1 kg weight. These robotic modules have independent controllers and actuators, and can communicate with each other in order to connect.

A subsequent study and first reconfigurable robot is PolyPod. Mark Yim [2] developed PolyPod in 1993 in the scope of his PhD, Yim showed that by connecting the two types of modules of the PolyPod in different ways. The PolyPod was dynamically reconfigurable, but was unable to change shape by itself. Mechanically, PolyPod is an important study to the class of chain-type modular reconfigurable robots.

CONRO is a good example of chain type modular reconfigurable robot modules. It was developed by Wei-Min Shen et al. [3] at the University of Southern California. Every module has two standard RC servomotors corresponding to pitch and yaw angles and it is self-sufficient and autonomous, because it has all computation hardware, batteries and sensors on-board. A disadvantage is that the connection mechanism, between the robot modules, is not genderless.

MTRAN is one of the interesting modular reconfigurable robot platforms which was developed by Satoshi Murata et al. [4, 5, and 6]. MTRAN has a hybrid architecture. It is good both mobility and reconfiguration performance. It is composed of two half of cylindrical parts and a link working as actuator with two DOF. Even though the two actuated axis are aligned in parallel which only allows rotations in one plane, multiple connection surfaces compensate this disadvantage. Also, there are three generation of MTRAN.

Unsal and Khosla [7] have designed I-Cube, a modular reconfigurable robotic system. I-Cubes is a two pieces modular reconfigurable robotic system. There are two different parts. One of them is three degree of freedoms active modules and passive connection elements. While attached to a cube on one end, links are also capable of moving themselves and another cube attached to the other end.

The ATRON is developed by Stoy et al. [8], Each ATRON robot module consists of two hemispheres where one can rotate relative to the other. Its design based on lattice module architecture. Modules can distribute power via their connecting mechanisms and use a power controlling system for voltage regulation and battery charge and maintenance.

In this paper we propose mechanical design steps of a new modular reconfigurable robot module which has five different active degrees of freedom having four revolute and one prismatic is called as OMNIMO [OMNIdirectional MOdular robot].

II. Mechanical Design

Robotics technology deals with the design, manufacturing, operation and application of robots as well as computational systems for their control. So, robotic systems are highly complex interdisciplinary technical machines. Hence, robotic systems require many different engineering fields knowledge that are highly connected and dependent of each other. Especially, mechanics, electronics and intelligent control have highly important role in robotic system design. During design of our robotic platform OMNIMO, these technical areas are considered with their importance and connectivity of each other. In the scope of this study design of OMNIMO is presented in four phases which are;

- Mechanical design
- Electronic system design
- Control software design
- Test and measurement

Both design and construction of electromechanical robotic systems especially modular reconfigurable robotic systems are challenging tasks. So many mechanical parts, electronic controllers, motors, sensors, cables and complementary mechanical and electronic parts are complicated to design and manufacturing of robots. Therefore, designing a robot (especially mobile and modular robots) is setting up the balance between size (mass moment of inertia and weight), motor and battery power. These three elements are inversely connected with each other. In other words, more battery power increases the weight and size of the robot and requires stronger motors, stronger motors increases size and mass either. So finding the optimum balance requires a lot of computation and trials also needs experience.

In this part, mechanical design details of OMNIMO and our robot design approach are presented. We can divide mechanical design into three phases. First phase is conceptual design, component selection and finally dimensional design.

A. Conceptual Design

We can define the conceptual design is a first phase of design. The conceptual design provides a description of the proposed system in terms of different ideas, design goals, requirements, limits, constraints and concepts about how the system behaves, and look like.

After deciding a build modular reconfigurable robot, we start the design of OMNIMO with the conceptual design as it should be. During conceptual design of OMNIMO, first of all we understand the state of art. More than seventy robots are investigated through scientific papers. After inspecting modular robot module and types, we observe that some drawbacks for example, single module moving capabilities are very low, also multi module robot configurations movements are not very smooth due to mechanical limitations of robots. By this point of view, during the conceptual design of OMNIMO, we have identified some requirements to improve self-mobility, flexibility, multi module productivity and diversity.

- Homogeneous module design in order to increase number of units
- Hybrid architecture to increase flexibility
- Three dimensional moving capability
- Increasing number of genderless connecting faces
- Increasing single module moving capabilities and locomotion
- Using both prismatic and revolute joints in mechanical architecture of robot module
- Data and information transmission should be in wireless between modules, in order to avoid connection faults
- Each robot module must be completely autonomous both power, computation and control.
- To increase human robot interaction a screen and speaker should be equipped.
- Computer based control should be possible for multi module robot control and swarm robot applications

These determined requirements also create our base of design criteria. Unfortunately these extra requirements increase the complexity of the system.

B. Component Selection

Component selection is second step of mechanical design and it should be completed before dimensional design (solid modelling). After identifying all mechanical and electronic requirements in conceptual design, all necessary mechanical parts such as

- Bearings
- Linear guides
- Gears
- Ball screw
- Shafts
- Couplings
- Flanges
- Screws and nuts

are selected and provided. Also all electronic parts which are

- Controllers
- Motors
- Screen
- Sensors
- Regulators
- Wireless communication unit
- Battery

are selected and provided. Robotic systems especially mobile robotic systems should be energy efficient, so size and weight of the robot should be minimum. Size and weight of the robot directly related to its components, because of that reason, all mechanical and electronic components are deeply searched nearly all on supplier's website and their catalog. We had come across two difficulties during component selection step. First one is size and weight of components and second one is their price. Because, powerful and compact components generally three or four times expensive than regular ones. We can say that, challenge of component selection part is selecting optimum parts with limited budget.

C. Dimensional Design

Dimensional design can be defined as visualizing of systems. Visualizing the design is an important aspect in order to verify the complete design intent. Recently, designers use CAD (Computer Aided Design) software for visualizing and three dimensional modelling. By helps of CAD software, designers can easily reach general appearance, functionality, total size, mass and mass moment of inertia information, structural strength, collision detection and assembly tests. During dimensional design phase main important aspect is manufacturing methods of non-standard mechanical parts. According to the manufacturing type, design of robotic system can be completely or partially changed. So, before starting dimensional designing, the designer should define manufacturing methods.

At the beginning of the study, main manufacturing methods of robot were chip removing processes that are milling, turning and laser cutting. Main material 7075 T6 quality aluminum. In spite of all the machines were CNC operated, we had a difficulty to produce highly detailed parts. So we tried to simplify, divide and enlarge the body parts. This time mass of the system made a trouble. Required motor didn't exist in order to actuate system. Eventually, our aluminum body solutions inadequate with accessible manufacturing machines. First manufacturing trials of earl prototype can be seen figure 1.

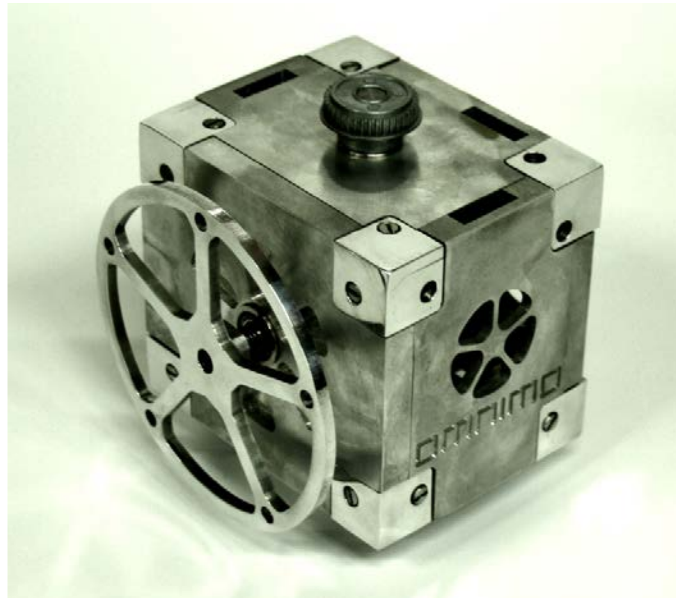

Fig 1. Early manufacturing trial of OMNIMO

The reasons which are mentioned previous paragraph, new type of manufacturing methods were searched and investigated. Finally, additive manufacturing was decided to use as a main manufacturing methods. Additive manufacturing or more popular name 3D printing is ground breaking machines which is a process of making three dimensional solid objects from a CAD file. The formation of a 3D printed object is achieved using additive processes. In an additive process an object is produced by laying down successive layers of material until the entire object is finished. Additive manufacturing is very suitable for low volume applications. Also, 3D printers give an opportunity about not manufacturable parts with traditional manufacturing techniques. There are a few methods in additive manufacturing and from plastic to titanium different materials can be used. However, there are some sort of drawbacks, for example durability and strength of additive manufactured parts are lower than the parts that are produced with traditional or chip removing process. Durable materials using precise machines are very expensive. Cheap machines produce structurally weak objects and poor surface quality. Also resolution is another critical criteria. According to the requirements and estimating advantages and disadvantages of different methods of additive manufacturing and various machines, FDM (Fused Decomposition Modelling) methods had been selected for producing body elements of robots. Body parts of second generation of OMNIMO were decided to produce with 3D printing from acrylonitrile butadiene styrene (ABS) thermoplastic material. 3d printing is selected due to keeping the idea of rapid manufacturing, scalable production, and multiple design iterations.

After discovering capabilities of additive manufacturing, design of second generation had been started. All spare parts had been drawn before body design and checked for conformity. Several designs had been developed simultaneously in order to reach high strength to weight ratio and we selected more robust one. After experimenting mechanical strength of some body parts we realized that we need to reinforce some critical points such as bearing beds, connection surfaces and force transfer elements with high strength aluminum alloy parts. They were designed and produced CNC milling machine by us. Our design approach had been shaped around minimum size (mass and inertia), structurally rigid, robust and open to development and additions. Second generation of design can be seen in figure 2.

Fig 2. Second Generation Design.

After finishing design, structural and functionality test in digital environment, we started to produce required parts. The printed parts of FDM type 3D printers, need post processing operations in other words, they need to be cleaned from rafts and support materials. Figure 3 shows cleaned 3d print parts of second generation. Second generation design of OMNIMO has nearly 500 parts with screws and nuts. Mechanic and electronic components of robots before assembling can be seen in figure 4.

Assembling operations of any mechanical systems requires assembling sequence and strategy. Designing compact and durable electromechanical systems need more complex assembly operations and sequence. First of all, some subassemblies were constructed such as gear box and ball screws and nut, electronic systems connected and tested before assembling to the system. Bearings were connected to their aluminum flanges.

Wiring also important problem especially complex and compact system. Control signal wires and sensor wires should not pass over high power systems such as motors and regulators. Wire transfer between moving blocks our robot, needed a special telescopic protector and it was developed by us. Subassemblies and full assembly of robot requires nearly 10 hours. At the end of the construction, robot ready to test and control. Appearance of second generation design can be seen figure 5.

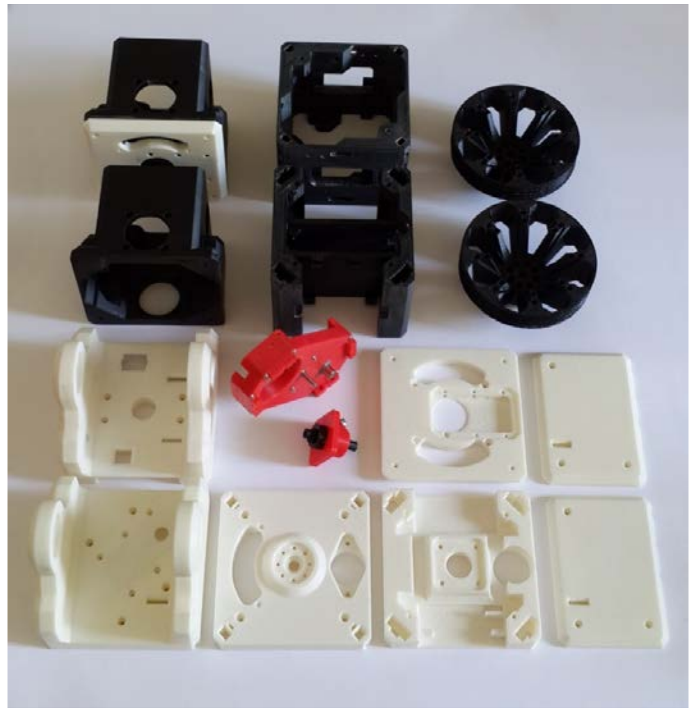

Fig 3. 3D Printed Parts of Second Generation Design

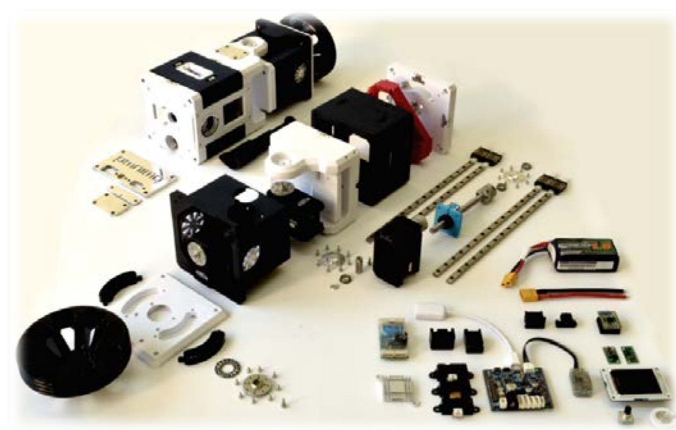

Fig 4. Unassembled Picture of Second Generation OMNIMO

After finishing mechanical assembly and integration of electronic system second generation of OMNIMO was ready to developed control software. OMNIMO designed and developed for realizing both mobile robots, robotic manipulators and their combinations. Because of that reason single module and multi module movement capabilities are very important.

Fig 5. Picture of Second Generation OMNIMO

Capacity of robots completely depends on mechanic, electronic and software abilities. Mechanics and electronic systems of second generation was perfectly working as expected. But we had encountered some small problems during test and control also some small electronic and mechanic requirements occurred which are;

- Graphic control screen computation load blocked the wireless control
- Some small crack appeared on robot body after 3 months tests.
- IMU (inertial measurement unit) necessity occurred in order to evaluate robot orientation.
- Cables made a problem due to complexity and narrow pass
- Voltage regulators needed to be changed with high current capacity
- Battery needed to be upgraded. In order to extend working time.
- A special algorithm needed for preventing energy consumption when robot is nonfunctional

In order to improve design and removing problems we had decided to start a new generation design. Third generation design was sitting on same design concept of second generation. However, we had some improvements which are;

- 3d printed body with 20% carbon fiber reinforced PETG filament in order to improve durability. This filament is perfect for parts which need high stiffness.
- Body parts of robot are applied paste, sanded and painted for good looking.
- New touch screen embedded with its own controller
- Improved cable ways to prevent cable tangle.
- Improved with higher current capacity voltage regulators
- A 9 axis IMU with embedded own microcontroller to calculate robot orientation with respect to neutral position.
- Battery is upgraded with more capacity and compact one

At the end of the three different prototypes development, we can define the OMNIMO as a modular reconfigurable robot module which can capable of realizing both mobile robots, robot manipulators and also their combinations. Each module is a completely autonomous robot. It has five independent degrees of freedom (DoF) which are four revolute and one prismatic to ensure more flexibility and re-configurability. Kinematic configuration of our robot module stands on RRPRR arrangement. Third generation design and DoFs of OMNIMO robot module can be seen on figure 6.

Motion capabilities of each axis is as follows. First and fifth axes can rotate 360 degrees and it can be used as wheel and joint. Second and fourth axes can rotate 180 degrees and finally third axes can expand and retract about 100 mm and it can be used as prismatic joint.

The main features and capabilities of OMNIMO robot module can be considered as follows.

- A 3D moving capability with single and multi-module
- It has both revolute and prismatic joint in one body and it is not encountered previous researches
- There are 10 different connection faces on each modules in order to ensure flexibility

- It has its own controller, battery, actuation mechanisms and sensory equipment
- It has five active, independent degrees of freedom and they can be used in fixed, free and actuated forms
- Each module is equipped with wireless communication systems
- Each module has a touch screen for easy control and error monitoring

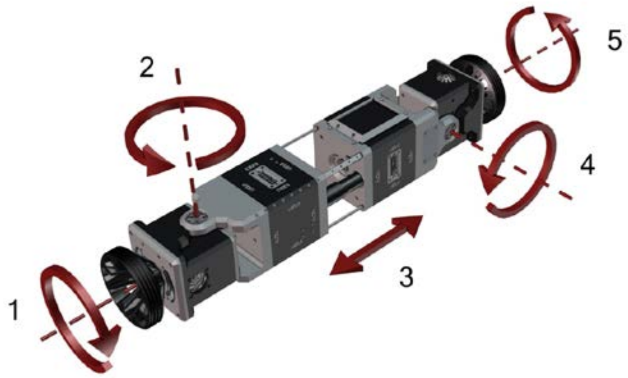

Fig. 6. Degrees of freedom of OMNIMO

Fig. 7. Photograph of third generation of robot module

III. Hardware Details

The motivation to build OMNIMO, shown in figure 7, was to develop open source, completely standalone, modular reconfigurable robot module with high dexterity and flexibility for multitasking. For this reason, robot module is equipped with so many hardware and a new kinematic configuration especially for modular reconfigurable robotic field. Since, performance of the modular robot is highly dependent on its mechanical and electronic capabilities. Mechanical part of robot, in each revolute axis double bearing (thrust and ball) are used except for motor bearings also 4 linear guide and rail to stabilize and make smooth the motion.

In order to actuate linear axis a ball screw-nut and a gear box are used. Details of the robot can be seen in figure 8. In electronic part, each axis of robot module is equipped with high torque robotic servo motor to ensure high precision positioning, position, velocity and torque (by limiting current) can be controlled in closed loop. 9 axis IMU (Inertial Measurement Unit, 3 axis gyroscope) to measure robot orientations (roll, pitch, and yaw angles). XBee wireless communication module to communicate other modules and host computer or master controller. Distance sensors are placed four side of the robot. Also our robot module is equipped with color touch screen to control the robot and error monitoring and bug removing purposes during software development. In spite of the hardware complexity, a compact and robust robot has been developed. The details of hardware list and physical data of robot can be found in Table 1. Figure 8 presents the positions of the hardware inside of the robot and internal structure in exploded view. Besides, electronic components connections and details are presented in figure 9.

IV. Conclusion

This paper presents mechanical design and manufacturing details of a new type, homogeneous hybrid modular reconfigurable robot module which name is OMNIMO. We have described mechanical design steps and hardware architecture of completely autonomous and compact robot module. We have confirmed that various kinds of robotic configurations are possible by proposed robotic module. Detail of the single module motion capabilities and potential multi module robot configurations can be seen in [1].

We have tested single module robot types and their motions in laboratory environments, on the next step we will test on uneven environments and situations in order to test mechanical durability of the robot module. However multi module robot configurations have only been tested in digital environments. After increasing number of module, test on real environment will be made and results will be presented.

Up to now three different prototypes have been produced. Latest developed robot module is very stable in mechanical, electronic and also in software parts. We are now working on hardware design of self-assembly docking mechanisms in order to improve self-assembling strategies and algorithms. After that we will increase number of modules to improve software for motion planning and self-reconfiguration ability.

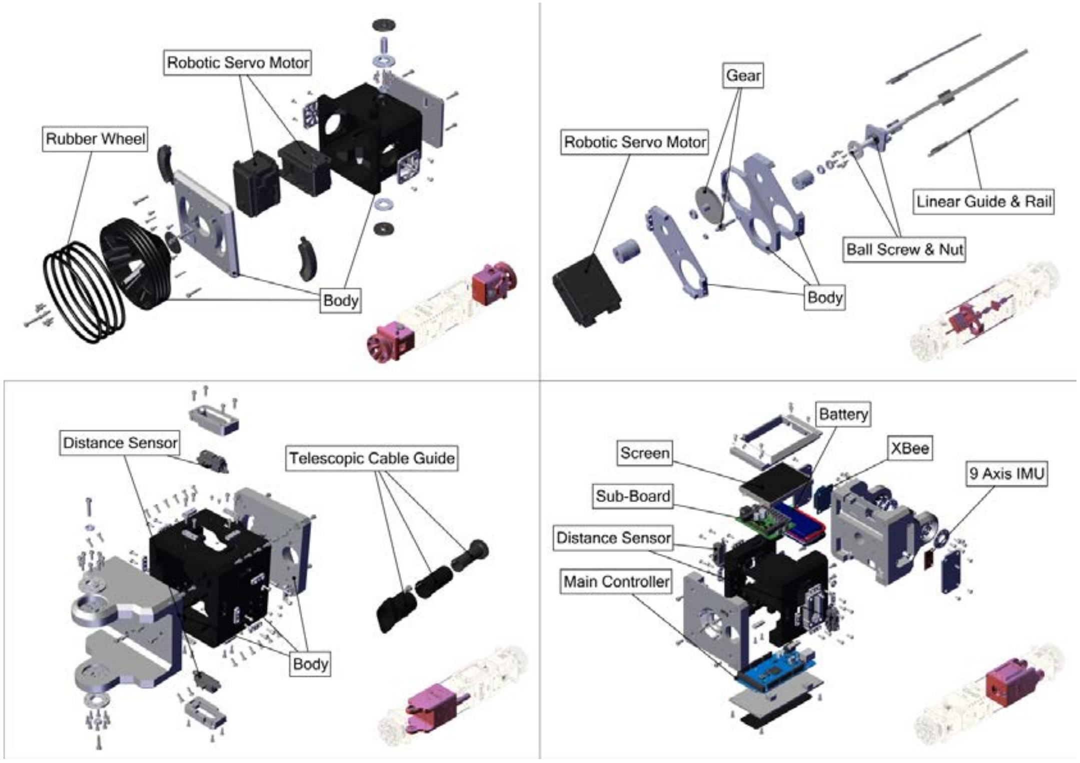

Fig. 8. Exploded view and internal structure of OMNIMO

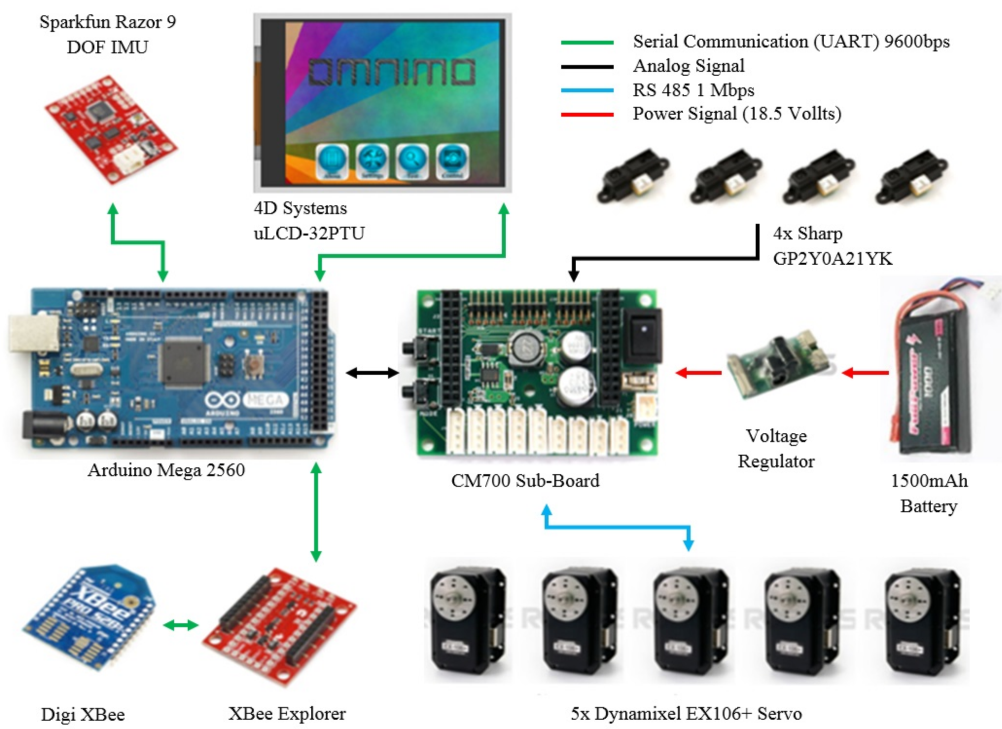

Fig. 9. Electronic components and connections of OMNIMO

Table 1. Physical and hardware specifications of OMNIMO

Size	105 X 105 X 590 mm
Weight	3200 g
Motor	5 X EX106+ [Robotis Dynamixel 106 kg.cm torque, embedded gearbox, voltage, current, temperature sensor and encoder]
Controller	Main: Atmega 2560, Sub [Screen] Atmega8, Sub [Motor] Atmega8, Sub[IMU] Atmega 328P
Wireless Communication	Digi XBee .Pro S2B
Screen	4D Systems uLCD-32PTU
Sensor	4 X Sharp GP2Y0A21 Distance Sensor Sparkfun Razor 9 Axis IMU sensor (3 axis gyro, 3 axis accelerometer., 3 axis magnetometer)
Battery	Li-Po [Turnigy 18.5 V, 1500 mAh]
Body Material	3D printed ABS and PETG (sanded and painted)

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