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MU-L8: The Design Architecture and 3D Printing of a Teen-Sized Humanoid Soccer Robot

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ABSTRACT— **The humanoid robot is a truly multidisciplinary research platform that gives universities the opportunity to combine electromechanical systems with artificial intelligence research. This paper describes the hardware and software architecture and 3D printing of MU-L8, or emulate, which is a teen-sized humanoid designed to learn and emulate human movements in order to compete in RoboCup soccer competitions. A contribution of this paper is the novel use of an iterative 3D design and printing process used to create a teen-sized humanoid. The conception of MU-L8 was inspired by the NimbRo-OP platform, which** encouraged **researchers to replicate the 95cm tall humanoid. MU-L8 expanded on the NimbRo-OP's template by employing SolidWorks-designed 3D printed limbs and a ROS-based control system. Cost of replication for MU-L8 would be comparable to buying a DARwIn-OP kid-size humanoid.**

Index Terms—Humanoid robots, 3D printing, robot soccer, ROS, RoboCup.

I. INTRODUCTION

The development of humanoid robotics platforms for research is a growing field [1][2][3][4]. In its simplest terms, humanoid robotics is a projection of the human body in hardware. The human body has the incredible ability to adapt and perform all of the tasks required by everyday life and the goal of humanoid robotics is to replicate these abilities and make improvements where possible. The motivation for these projects is the potential void humanoid robots can fill in the human society. For example, humanoid robots could provide assistance in rescue initiatives or hazardous situations and even with public service duties. As advancements continue we may discover, there is no limit to roles humanoid robots can play in society. The Marquette University (MU) Humanoid Engineering & Intelligent Robotics (HEIR) Lab team has created MU-L8 for research in designing socially intelligent robots [6] and for competition in the teen-sized RoboCup humanoid robot soccer league [7][5]. MU-L8 was inspired by the NimbRo-OP teen-sized humanoid and we describe their relationship in this paper. MU-L8 is being designed as a candidate to compete in the RoboCup Teen-Sized Humanoid Robot Soccer Competition with aspirations for RoboCup 2014.

The rest of this paper is organized as follows. We discuss related work including existing humanoid research platforms and other 3D printed robots. We then discuss the implementation of MU-L8 in three main topics: the hardware design and kinematics, the networking of robot components and the ROS-based software architecture.

II. RELATED WORK

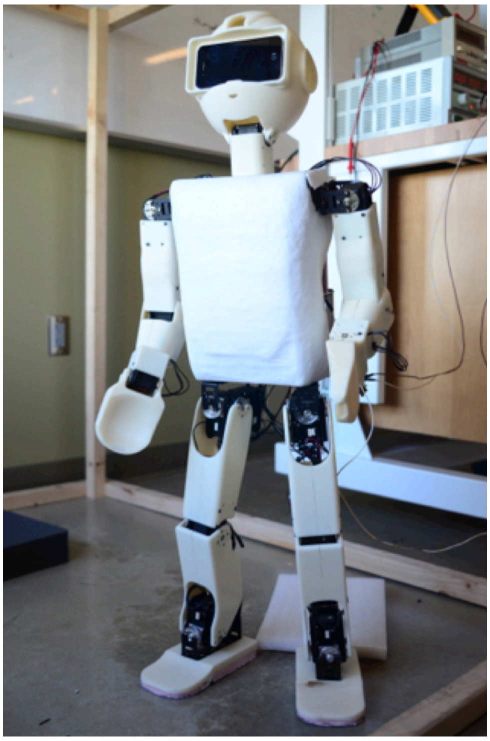

Fig. 1. The MU-L8 prototype

The NimbRo-OP [3] was developed at the University of Bonn and expanded upon by implementing modified DARwIn-OP software. The open source community that is fostered by RoboCup allows robots like DARwIn-OP, NimbRo-OP, and MU-L8 to build upon each other's innovations to advance their research. The release of the NimbRo-OP and DARwIn-OP were important to the open-source community because they allowed universities to purchase a $12K-$20K USD humanoid platform for developing their own software, mechanical, or electrical research. The HEIR Lab team is building MU-L8 with the intention of bringing another unique innovation to the international robot community through Robocup in order to contribute to ongoing research in multi-robot systems and human-robot interaction (HRI).

One of the main innovations of our work is the use of a 3D printer to create the limbs, hands, feet, neck, and head of our teen-sized humanoid robot. Recently, 3D printed robots have been used for research and educational purposes. Using 3D printers to build a robot has its advantages such as the ability to replicate complex engineering parts from design files that are easily shared over the Internet [8]. 3D printing, or additive manufacturing, is the process of digitally fabricating a 3-dimensional object and successively adding layers of material to create the object [18][19].

The DARwin-OP robot, which is a popular kid-sized robot for RoboCup is sold by ROBOTIS for 12K USD[10], has been replicated using a 3D printer and open source CAD files. The 3D printed version is estimated to cost the builder around $6K USD to make [9]. This is an example of how the DYI (Do It Yourself) community is using 3D printing to bring robotics development within the reach of a modest budget.

This is how the Miniskybot was built, through low cost 3D printing. The Miniskybot uses 3D printed parts, two modified hobby servos to create a differential drive robot [8]. The goal of this 3D printed robot is to show students how to make an affordable robot and then they would be able to improve its design as needed. This robot is purely for educational purposes.

Another example of another of 3D printed robot used for research is at the Biomimetic Millisystems Labs at UC Berkeley. They built STAR (Sprawl Tuned Autonomous Robot) [11], which resembles a small insect. The STAR tries to mimic animal movement, sensing, dynamics, and control strategies. The purpose of robots like STAR is to eventually deploy them in search and rescue missions.

II. HARDWARE DESIGN

MU-L8 measures 91.5cm tall and weighs 7.6kg. It has 24 total DOF provided by Dynamixel servos. Each leg has six MX-106T actuators; each arm has three MX-64T and two MX-28T actuators. The neck has two MX-64T actuators. All limbs are 3D printed ABS plastic and the torso is machined aluminum.

A. MECHANICAL DESIGN

We designed MU-L8 to be 3D printed from ABS plastic so that others may easily replicate the robot and use it as platform for their own research. To encourage replication, we considered the affordability and availability of building materials, including off the shelf electronic components. Social interactivity was another important consideration because we will use the robot for HRI (human-robot interaction) research in addition to RoboCup competition. To satisfy social interactivity, the head of MU-L8 was designed to accommodate a smartphone (e.g. an Android OS-based phone), which will interact socially with a user through speech recognition, generation, and facial expressions. This Smartphone Intuitive Likeness and Expression (SMILE) device will also have a mode for touch-based user command entry to configure and control the robot.

It was important that the central torso be made of durable aluminum to protect the computer stack. We modeled the torso off of the NimbRo-OP torso with modifications to simplify the design, as shown in Figure 2, so that a student would be able to easily build it in a standard machine shop. The torso was machined from common 3mm thick aluminum sheets for component shelves and the uprights were made from 9.5mm square rods. Figure 1 shows MU-L8 with an encased torso that was made from molded thermoplastic for protection and aesthetics.

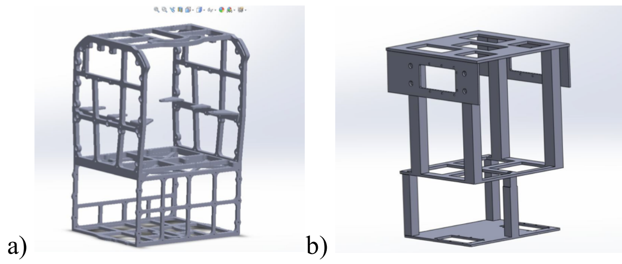

Fig. 2. a) The NimbRo-OP's torso design [12] was modified to b) in order to simplify the building process so that a student with access to a standard machine shop could replicate it.

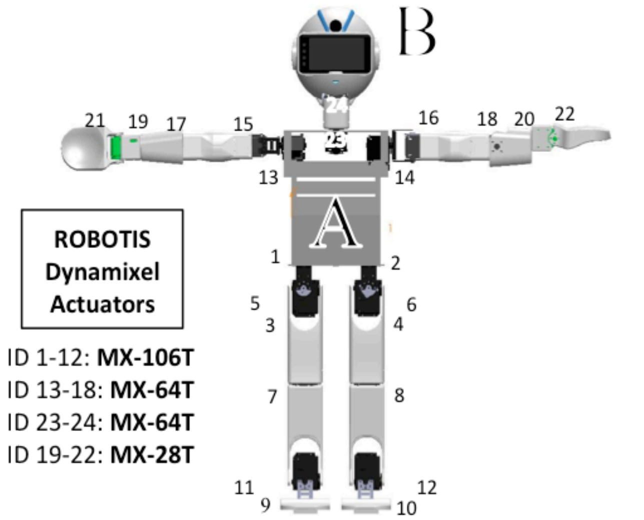

Fig. 3. A) The torso holds the on-board computing components and power supply. Computing components consist of a Zotac nano XS AD12 and BeagleBone Black microcomputer. Power is supplied by two 14.8V 4800mAh Li-Po batteries, which rest above motors 1 and 2. B) The Logitech C905 720p webcam is housed in the head along with an android phone used for social interaction.

To fasten one motor to another, we purchased aluminum brackets from ROBOTIS [10]. There is a HN05 in each shoulder that connects motor 13 to 15 and 14 to 16, as shown in Figure 3. The HN08, shown in Figure 4, is a larger frame that holds 2 perpendicularly oriented MX-106 motors. This setup is found in each hip and ankle to allow smooth abduction and extension of the legs and feet.

B. 3D Design and Printing Process

There are several challenges associated with 3D printing. Strength and support are the most important aspects since playing soccer places punishing force on the robot's frame. For this reason we designed each part to withstand significant torque and impact.

The process of designing and prototyping and testing each limb was crucial in meeting the torque and impact criteria mentioned above. The prototyping process, shown in Figure 5, began with simply designing the limb around the Dynamixel motors. Once the initial prototype was printed using a Dimension ES1200 rapid prototyper, we could see how the limb performed on the robot. Tests usually exposed design flaws that affected either the strength of the limb, ease of assembly/disassembly, or restricted movement. The limb was then redesigned to correct any flaws before printing it again.

C. Kinematic Analysis

The kinematic model is the foundation of this system. The Denavit-Hartenberg Method will be used to create the kinematic model. We first developed a physical model and then applied simplifying assumptions to obtain the mathematical model. The physical model of MU-L8's right arm is described using the Denavit-Hartenberg (DH) parameters θ_n, α_{n-1}, a_{n-1}, and d_n are used to describe the arm.

The Denavit-Hartenberg method is commonly used for robotics modeling and the specific approach used here is proximal-variant. In Equation 1, the homogenous transform describes the locations of the joints in the right arm, shown in Figure 6, using the DH parameters in Table 1. This method is applied to all joints of MU-L8, allowing us to graph its movements using forward or inverse kinematics.

Future research will include a dynamic analysis of MU-L8's movements, which will strengthen our ability to control the humanoid. We continue to explore control methods, such as state-space or other advanced control techniques using simulations.

Table 1. Right Arm DH Parameters

	Link Parameters Right Arm			
Joint n	θ_n	d_n	a_{n-1}	α_{n-1}
14	0	0	0	0
15	0	0	0	90
16	-90	0	L12	-90
17	0	L13	0	90
18	0	0	0	90
19	0	L15	0	-90

- Full Right Arm Transformation

T1319=

$$\begin{bmatrix} -0.448 & -0.401 & -0.799 & L12 - 0.799 * L13 - 0.799 * L15 \\ -0.849 & 0.201 & .401 & 0.401 * L13 + 0.401 * L15 \\ -4.49e\_17 & 0.894 & -0.448 & -0.448 * L13 - 0.448 * L15 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

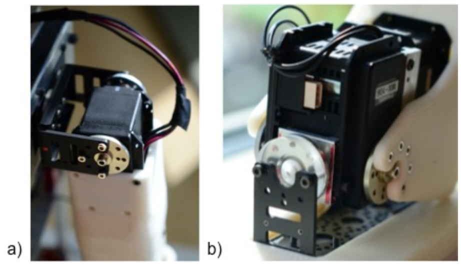

Fig. 4. a) HN05 and b) HN08 brackets were slightly modified by removing material to allow unrestricted hip and ankle movement.

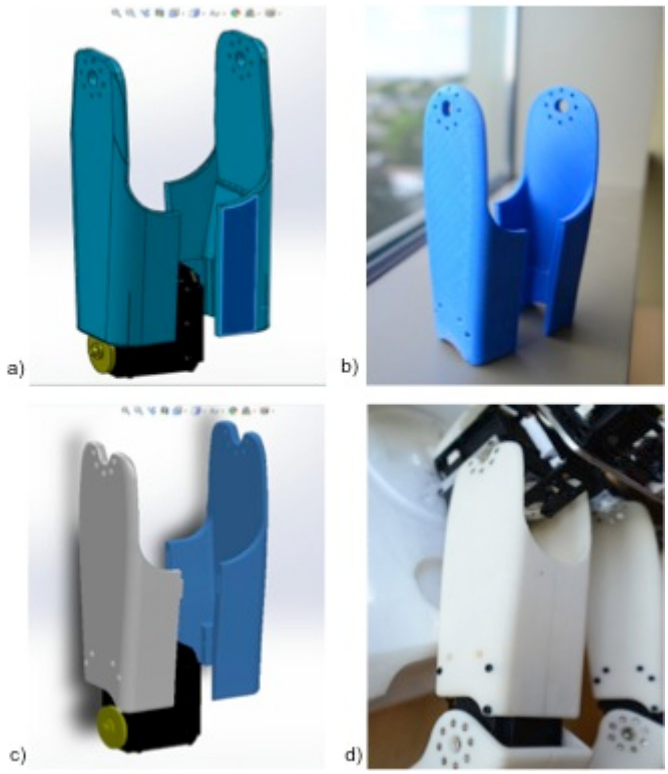

Fig. 5. a) The initial design of the upper leg in SolidWorks. b) Prototype of initial design. c) The improved design of the upper leg corrected several flaws of the initial prototype by featuring biscuit-type joints for assembly, more clearance for movement at both the hip and knee, and better fastener leverage on the actuators.

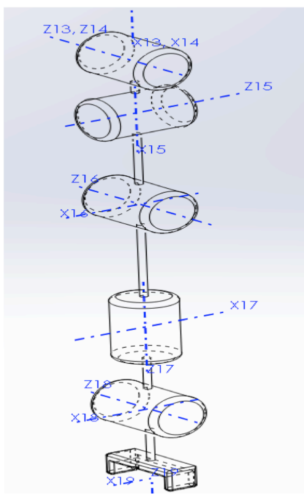

Fig. 6. Five DOF Right Arm

III. SOFTWARE ARCHITECTURE AND NETWORKING

The embedded system in a robot controls communication between actuators, sensors, and other devices, allowing the hardware to communicate with higher-level software. The hardware used in MU-L8 consists of a Zotac mini-PC, a BeagleBone Black sub-controller, Dynamixel Robot Actuators, Microsoft Kinect, Logitech webcam, 2-axis gyroscope, and 3-axis accelerometer. A detailed description of each component is shown in Table 2. The Microsoft Kinect will be removed for RoboCup competitions, but it is included in the design of MU-L8 for human motion tracking and learning purposes related to our humanoid health coach research [13].

ROS (Robot Operating System) is a meta-operating system commonly used in robotics [14]. It was chosen as the high-level operating system for MU-L8 over other robot operating systems, software architectures, and development environments, including Player, Microsoft Robotics Developer Studio and the initial NimbRo-OP, and DARwIn-OP software architectures. The open-source model of ROS provided the greatest amount of community support and largest libraries for the robot operating systems researched.

A. *NETWORKING AND SOFTWARE CONSIDERATIONS*

The Zotac mini-PC is the main controller that controls image processing, motion planning, localization, and other high-level functions. This processor was chosen based on its robust computing power and compact design. It seamlessly sends advanced motion commands through a crossover Ethernet connection to the sub-controller, which communicates with the actuators and receives data from inertial sensors. The overall component network is shown in Figure 7.

The sub-controller regulates simple motion commands such as walking and getting up from a fall by sending signals to individual actuators. It also publishes the robot's position to the mini-PC to be used in conjunction with the kinematic model.

Initially, the ROBOTIS CM-700 served as the sub-controller between the mini-PC and the motors. However, the CM-700 could not communicate with both ROS and the motors concurrently, which is an essential feature of ROS, so we experimented with the more general purpose BeagleBone Black, a Linux-based developmental microcomputer. It serves as a versatile sub-controller because it can connect to all motors through a ROBOTIS USB2Dynamixel connector while receiving data from the gyroscope and accelerometer using built-in GPIO pins [15].

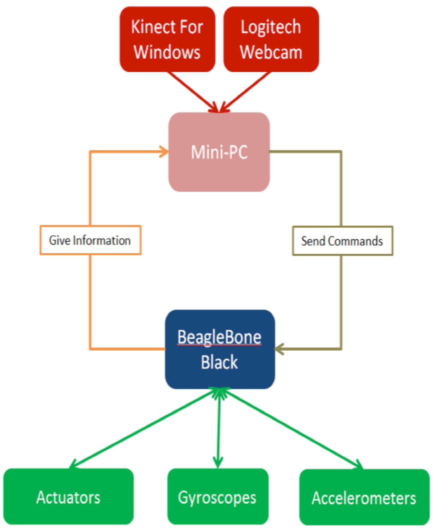

Fig. 7. Data is communicated between the mini-PC (main controller) and the BeagleBone Black (sub-controller) at a rate of 1Gb/second. The Kinect and Logitech webcam are both connected to the mini-PC through USB.

TABLE 2. A list of each component's technical specifications.

Category	Description	Specifications
Dimension	Height Weight	91.5cm 7.6 kg
DOF	Head Arm Leg	2 5 6
Main Controller	CPU RAM Disk Network USB Port	Zotac dual-core 1.7GHz AMD 4 GB 32 GB SATA SSD WiFi-Ethernet x4 USB 2.0, x2 USB 3.0
Sub-controller	CPU Frequency Flash Memory SRAM	AM335x ARM Cortex-A8 1GHz 2 GB and micro-SD slot 512 MB DDR3
Actuators	Voltage Communication	12~14.8 3 PIN TTL
Sensors	Gyroscope Accelerometer Camera	2 Axis 3 Axis Logitech C905 720p
Software	OS Framework Language	Ubuntu/Linux ROS C++/Python

B. *SUPPLYING POWER TO MOTORS*

Overheating of hip motors was a problem that occurred during the initial testing of the Dynamixel actuators. According to the method recommended by ROBOTIS, the actuators are to be daisy-chained together. This scheme unnecessarily heats up the actuators that lie between the power source and the end actuator. To avoid this problem we implemented a power bus scheme [16], shown in Figure 8, in which the power and ground bypass each actuator and current is taken from the bus as needed. The data connection still used the daisy chain protocol.

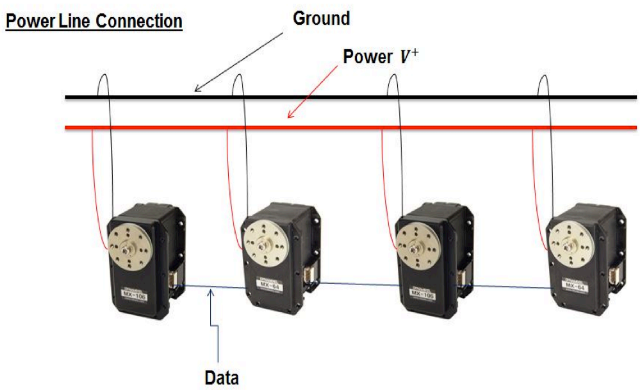

Fig. 8. This power supply scheme utilizes a power and ground bus to avoid overheating the motors.

IV. Future Work

The first priority for the MU-L8 project is to design and build a teen-sized humanoid that is capable of playing soccer autonomously in RoboCup. This is an important goal for the MU-L8 team, because we would like to participate in the learning and research collaboration that is fostered by the RoboCup community. To qualify for RoboCup, we must first further develop MU-L8's motion and locomotion capabilities in order to meet the qualifying requirements along with the completion of vision, localization, and decision-making algorithms. This research is ongoing and these topics are the subject of future papers and summarized in the forthcoming RoboCup technical report application.

Future research on the MU-L8 project includes development of full body emulation of human movements using the Kinect. We are able to achieve limited upper body emulation on the Nao humanoid platform with open source code based on ROS.org [17]. The next step is to reconfigure these algorithms to fit MU-L8's kinematics. The full body emulation capabilities of MU-L8 are expected to be functional within the next year in order to contribute to current research in the HEIR Lab.

V. Conclusion

In this paper, we introduced MU-L8, a teen-sized humanoid robot that was built mostly from 3D printed plastic in a standard machine shop. MU-L8 is a unique advancement in the area of robotics research because of its ease of replication, low cost components relative to other comparable humanoids, and its employment of open-source ROS. MU-L8 is also a beneficiary of the open source contribution and release of NimbRo-OP by the University of Bonn and is an example of how the NimbRo-OP is opening the door to other universities to build humanoid robots for research and competition in RoboCup. We plan to release our software advancements to the open-source community after qualifying for and competing in RoboCup.

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