ADJUSTABLY DESIGNED TORQUE CONTROLLED HUMANOID PLATFORM

[1]JEESEOP KIM, [2]YUKI OMORI, [3]ASHRARUL H. SIFAT, [4]TOMONARI FURUKAWA

[1,2,4]Dept. of Mechanical Engineering Virginia Tech
[3]Dept. of Electrical Engineering Virginia Tech
E-mail: [1]Jeeseop@vt.edu, [2]omori@vt.edu, [3]ashrar7@vt.edu, [4]tomonari@vt.edu

Abstract- Since Darpa Robotics Challenge, the research topics for the humanoid operation which includes balancing, whole body motion, multi-contact control, human-robot interaction is getting more interested. Unfortunately, many high performance humanoid research platforms have difficulty in maintenance, modification, and operation because of its own system complexity and irrational price of the components. Several small platforms which have an affordable price are possible for the research. But the small platform itself cannot be a suitable platform for studying torque control because of its low sensor resolution and extremely low value of the physical effects. In this paper, we introduce ATHENa, an affordable, fully torque controlled full size humanoid platform. The proposed humanoid platform design is not only possible to adjust design, but also easy and safe to operate. The skeletal structure of the platform also supports the unconstrained cover design and any additional structure. We describe the mechanical structure and electrical system of the platform, and we present the design parameter guideline for easier modification of the design.

Index Terms- Robotics, Humanoid, torque controlled platform, adjustable design.

I. INTRODUCTION

The Darpa Robotics Challenge (DRC) was inspired by the disaster that human cannot deal with it because of the hazardous situations. The high performance humanoid platforms such as ATLAS, ESCHER [1], HRP-2 Kai [2] were proposed to overcome the hazardous situations that is impossible for human body to overcome. For the purpose of overcoming harsh environment which is occurred in the infrastructure for the human, the high performance humanoid platform had enormous power actuating system and adult human size and ratio [3]. These power and size was good for overcoming harsh environment occurred in the infrastructure for human, but that features became another threat for the researchers. At least two people were necessary for operating the high performance humanoid, and even if more than two people kept an eye on the operating process, it was still hard to stop the unexpected situations, prevent loosing balance, and catch the humanoid before fall. Additionally, those features also easily became a threat for the humanoid platform itself. Impact of fall was bigger than expected because of its weight and height. For these reasons, preventing unexpected motion [4] [5], balancing with unexpected external forces [6] [7], and balancing analysis during contact state [8] were applied to propose more stable humanoid operation. But these solutions could not protect researchers perfectly because its high performance hardware always could be a threat to human. Another thing to consider is that the high performance humanoid platform has high complexity in their system. For achieving the purpose, the high performance platform includes expensive sensors, actuator system and customized system structure for the best performance. These features of the platform also make it difficult for user to operate and maintain. To protect the vulnerability of the system, and to avoid expensive maintenance cost, the study proposed the protection from the impact [9] in the hardware point of view. But the solutions to protect from the impact is not a permanent protection, and still introducing the new high performance humanoid platform for the research is sometimes not a reasonable choice. ATHENa (Adjustably designed Torque controlled Humanoid for the Environment of Navy) that we propose in this paper aims to fill the area

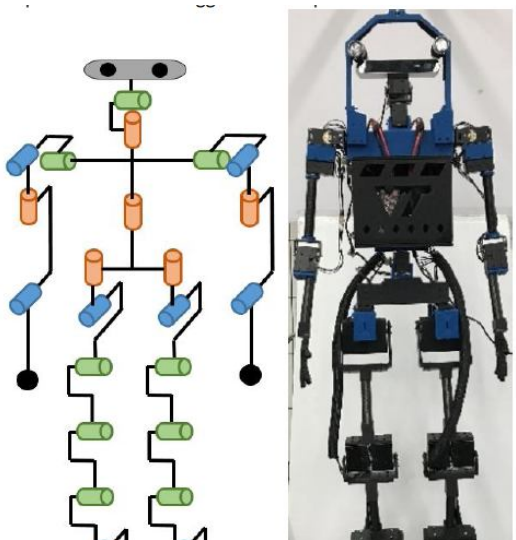

Figure 1. ATHENa: Kinematic structure and appearance of the robot

of affordable torque controlled humanoid platform with adjustable design without compromising the performance. We also introduce both the design parameter guideline that can make maintaining process easier and shorter and the software structure that makes it easy for the user to operate. The humanoid platform with its kinematic structure is shown in Fig. 1.

Table 1. ATHENa Specifications

Feature	Specification	Value
General	Height & Weight	1148mm, 12.02kg
	Material	ABS, CFRP
	Battery	3-cell LiPo(12.0v, 4000mAh)
PC	Model	GB-BXi7-5775
	CPU	Intel Core i7
	Memory	8GB DDR3 RAM, 120GB SSD
Interface	Model	FTDI Board
	Converter	USB-COM485
	Speed	3Mbps
Actuator	Model	XM540-W270-R
	Stall torque	12.9N.m
	No load Speed	37rpm
Degree of Freedom	Total	23
	Legs	6 + 6
	Arms	4 + 4
	Waist &Neck	1, 2
Sensor	Encoder	4096/rev
	IMU	3DM-GX3-25
	Camera	Xtion Pro Live
	Camera sensor	2*RGB, 2*Depth

II. HARDWARE DESIGN

We focused on Proposing a torque controllable child size humanoid design that small group of researchers or individual researcher also can use for research easily without any danger. For that purpose, features like easy assembling, handling, and fixing were considered during designing. For the overview of the main hardware, information of the specification of the main hardware components are introduced in Table 1.

A. Mechanical Structure

For easy using and less danger platform, we mainly considered the method that can decrease the weight of the humanoid. To make the lightweight design, Carbon Fiber Reinforced Polymer(CFRP) tube and Acrylonitrile Butadiene Styrene(ABS) for 3D printing were used in ATHENa. Especially, CFRP tube was selected for each link because of its high strength-to-weight ratio and rigidity.

Light materials also allowed the less power actuator for performing dynamic motions. Actuator module only needs the torque sensing for torque control. In ATHENa, only one COTS(Commercial off-the-shelf) type actuator was used not only to avoid system complexity but also to reduce the total cost of hardware. Two actuators are used together in each joint if the joint needs higher torque than possible torque of the actuator. Torque amplifying mechanism was not considered because adding torque amplifying module induced non-collocated control which is less stable than collocated control. [10]

The other point that we considered is the easiness of maintenance. During the research, the humanoid platform is always exposed to the risk of breakdown. But the design for decreasing the impact makes the hardware

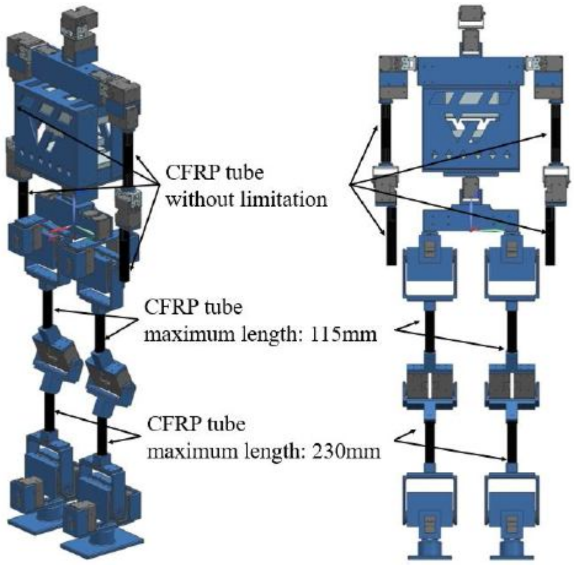

Figure 2. Description of the CFRP tube design parameter. Blue colored part: 3D printed. Black colored part: CFRP tube

heavier. Also the design for protecting the system structure can become more complex. All of these features always make the maintenance more complex. Thus, we proposed the design concept not for avoiding or absorbing the risk, but for easy repairing. As depicted in Fig. 2, the connectors between links and joints were designed using 3D printer for using the CFRP as a tube only. Even if each part is broken, printing the connector or buying the COTS type CFRP tube is the only thing for repairing. Second, to avoid the confusion, every screw for assembling have the same dimension.

B. Adjustable Design Parameter

In the design of ATHENa, we proposed the design parameters that can be chosen for its purpose. Also we proposed the boundary of the design parameters to avoid design parameter coupling, which helps making customized ATHENa more easily. This characteristic can be used for ATHENa platform to satisfy the various research scope.

As introduced before, CFRP tube is used for each link of ATHENa. The length of the CFRP tube with the same diameter is the design parameter that can be chosen. Two CFRP tubes are used in each arm and leg. The length of the tubes used in these parts can be chosen. Each leg consists of thigh part and shin part. The maximum possible CFRP tube length is 115mm for thigh part because of the limitation of the torque in the knee joint. The length of the shin part can be longer 115mm than the length of the thigh part. The validation of this length value is introduced in part IV. The length of the tubes used in the arms can be chosen freely. These limitations are the theoretical boundaries of each link. For the appearance of the humanoid, design ratio should be evaluated using the common known human body ratio, especially child.

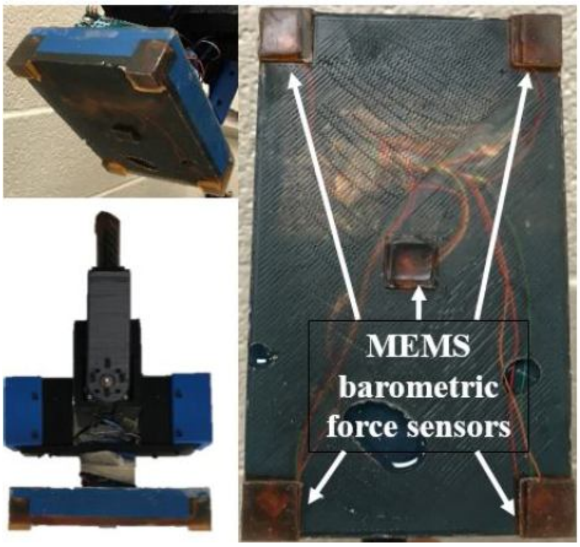

Figure 3. Configuration of the pressure sensor on the sole and appearance of the proposed sensor system module

Each CFRP tube can be regarded as a skeletal structure of the robot. Unlike external-skeletal structure, there is no need to analyze the rigidity of the external design. Every external structures, includes cover, can be added easily. The one thing that needs to be considered is that, the external structure which is near the knee joint needs to be covered by the virtual tube which has same center with the CFRP tube, and 40mm diameter for avoiding self-collision.

The dimensional tolerance needs to be considered carefully in the 3D printed parts because of the features of 3D printing mechanism, especially for the part used for the assembly. We classified and introduced dimensional tolerance that can help to avoid design parameter coupling and assembly problem. The CFRP tube assembled position needs to have 0.4mm bigger diameter than the diameter of CFRP tube. Screw holes also needs to have 0.4mm bigger diameter than the diameter of the screw. Every distance between the parallel plane in the concaved 3D printed part needs to have 0.25mm longer distance than its original design.

C. Footpad Design

One of the main stability criteria of the humanoid is Zero Moment Point (ZMP) which can be measured using force and torque applied at the sole of the foot. Common FT sensor for the measurement which is using for the high performance robot is really expensive and hard to maintain when it is broken. For this reason, the new sensor system using five MEMS barometric pressure sensors at the sole of the foot is proposed in the ATHENa platform [14]. The configuration of the sensors on the foot is described in Fig. 3. Takktile, developed by Righthand Labs [15], is chosen for the pressure sensor for the new sensor system. The detail wiring between each sensor and processor is described in Fig. 4. I^2C protocol is used for chip to chip data transfer in serial because of its

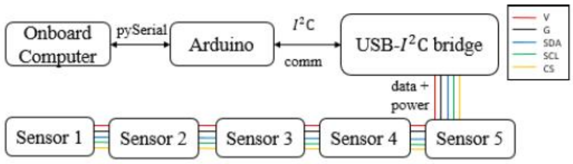

Figure 4. Connection diagram of the pressure sensor system

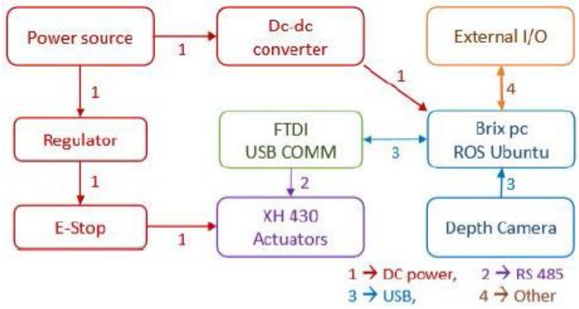

Figure 5. Mechatronic system of ATHENa

high speed. Arduino is used as a data processing device with the onboard computer in ATHENa.
This proposed sensor system has much more rational price and easy to replace when the system is broken because of its modular structure. One more specification of the proposed sensor system is that, combining with elastomer and Takktile sensor helps user to tune the range of sensing. Casting 16mm elastomer would give the range of 15-16N and 22mm would give us around 33-35N for each sensor [14]. This range is sufficient for the current application of ATHENa. Thickness of the elastomer can be tuned by the purpose of the hardware.

D. Robot Electronics

The most important feature in the electronic design is to achieve simplicity without compromising the performance, reducing the cost as much as possible, modularity and fault handling capability. The heart of the mechatronic system is the Giga-Byte Brix computer with the Intel® Core™ i7-5775R processor which can operate at a maximum frequency 3.8 GHz. The specification in details is given in table 1. The flexible 3D printed torso has been designed to accommodate this CPU.
The communication and control with the Dynamixel XM540-W270-R actuators are established on the RS-485 bus through the FTDI USBCOMM board which has 4 ports each for connection of daisy chains. The daisy chain command interface is implemented in

joint torque controller packages which are directly controlled from the Linux based ROS packages.
In this aspect, the daisy chain implementation was tested also with the typical CM740 Dynamixel sub-controller which is a common choice in affordable humanoid robots [11][12]. But that platform was disregarded due to the effect that it provides no additional benefits and adds complexity to the mechatronic system. Therefore, the control is directly implemented through ROS controllers via a 3Mbps communication bus. The overview of the

Figure 6. Snapshot of the ATHENa in the Gazebo simulation environment

mechatronic system is given in Fig. 5.
The actuation method is rigorously focused on synchronization of adjacent actuators in a joint. Otherwise there will be undesired torsional movement in the joint and it will reduce the stability and lifetime of the joints significantly. The synchronization is done by manipulating the packet communication structure of Dynamixel protocol 2.
This however introduces a lag in operation as it waits for the all the actuator to receive their respective commands and then executes it at all at once. This synchronism can be relieved if a master-slave structure was adopted for adjacent joint actuators which is a future plan for this platform.

The power source of this system are LiPo batteries of 12V and 4000mAh. The batteries are connected to the actuators via SMPS2Dynamixel regulators distributed by Robotis. The sensors configuration in Dynamixel XM540-W270-R actuators can give position, velocity and current feedback. Moreover, for the robot state estimation, the 3DM-GX3-25 Inertial Measurement Unit (IMU) was additionally used and the contact forces are estimated using a novel tactile sensor configuration.

III. SIMULATION ENVIRONMENT

We proposed the simulation environment based on Gazebo simulator which is described in Fig. 6. Commonly Gazebo simulator is nicely worked based on position controller. But our humanoid platform control framework is designed to calculate the desired torque for each joint. Thus, we tried two control scheme in parallel. One is using joint effort controller in the simulator as a joint torque controller, and the other is sending the manipulated desired joint torque value to the position controller in the simulator. The first one is good for evaluating the joint response individually, and also helps to decouple the effect of each joint response from the motion of the robot. The second one is good for evaluating the whole body movement motion before operating the hardware. It also helps to find out and avoid the unrecognized weird

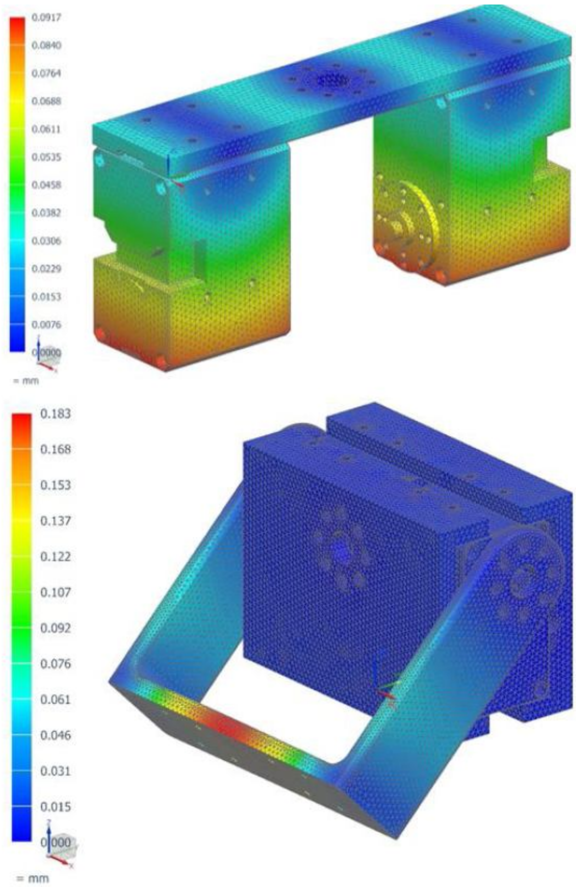

Figure 7. FEM analysis for the joints. Upper joint: roll joint, Lower joint: pitch joint

configuration point during modifying and testing the controller.

IV. RESULTS

The materials used in the design is ABS, and CFRP which helped reducing the total weight of the humanoid. The tolerance information was supplied with the proposed part design using ABS, and the COTS type CFRP tubes were used for humanoid design. These points help not only reducing the danger during the test using the ATHENa platform, but also manufacturing progress of the ATHENa platform easier. Thus, platform can be used for research without considering system breakdown, and repairing cost. Also, the platform can be maintained without spending a lot of time.

The suggested tolerance guide and adjustable design parameter also helps adjusting ATHENa platform. There are various environments that research topics want to focus on. Modifiable design parameters of ATHENa helps focusing on the various environments without considering the matching between the humanoid form factors and the dimension of the environments. Proposed design parameter guideline also helps avoiding design parameter coupling and complex consideration for the workspace of the humanoid. Fig. 7 describes the result of FEM analysis of the joint in ATHENa design. Roll joint and pitch joint design is analyzed by FEM because those two joint axis receives the highest torque when operating the humanoid. The simulation condition assumes the maximum length of the moment arm which is introduced in II-B, and maximum load which is identical with the whole humanoid weight. As a result, the maximum deformation of the roll joint is 0.0917mm and the maximum deformation of the pitch joint is 0.183mm. This FEM model is assuming that there is no additional structure to decrease the deformation. But the real design of the ATHENa platform already includes the reinforcing structure of these deformed part. Deformations are regulated less than the result of FEM analysis because of these additional reinforcing structure design.

The proposed sensor system for the foot also reduces the total price of the ATHENa platform without compromising the performance of sensing the force and torque applied at the foot. This sensor system basically helps researchers to control the stability and measure disturbance which are getting into the humanoid platform. Also, adjustable thickness of the proposed sensor system helps making perfectly fitted humanoid platform for each researcher.

The humanoid is high degree of freedom system. Thus, the connection of each actuator, and finding the proper place of each electrical component is one of the main design consideration. We focused on proposing less complex system, and intuitive connection between electrical components. To reduce the system complexity, one type of the actuator is used for consisting each joint. Two actuators are used together in each joint if the joint needs higher torque than possible torque of one actuator. Also, for the intuitive connection, daisy-chain connection is used for each limb, and the main computer controlled four daisy-chain connections in parallel. The wire connection extender is also used in the connection between joints because of avoiding the wire broken during the unexpected weird motion near the singularity. This feature also makes the maintenance and repairing easier.

CONCLUSION

The proposed ATHENa platform is the new concept of the humanoid platform for the research. Proposed platform has a child size height but it has lightweight. The lightweight is the feature that can reduce the risk of human injury even if the unexpected motion and the situation of losing the balance is occurred in the platform. Also, the low power actuator can be used because of the lightweight design. This feature can reduce the afraid of grasping the near joint part during operation.

The platform also has simple mechanical structure and focusing on easy manufacturing. Additionally, not only the mechanical system design but also the electrical system design was also focused on making easy maintaining system. Thus, even if the fall down or critical broken is occurred to the platform, repairing or changing the broken mechanical, and electrical part will be an easy task.
The platform can adjust its design easily without additional consideration. The paper proposed the critical guideline that can help avoiding the designing problems. Thus, the proposed platform can adapt various research purpose without laborious design modification process.

We also focused on proposing the user friendly controller with good performance. Its performance is perfectly fitted with the purpose of studying torque control at now. And we are in the progress of implementing the whole body control, and multi-contact control. We will continuously introduce the state of the art control framework periodically.

We will release all necessary design guidelines and 3D printable CAD files [16]. We hope that this design would contribute the various research, and development of the advanced humanoid control framework.

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