An Alternative Open Architecture Controller Design for the Bioloid Humanoid Robot

'Aqilah Zainuddin, Badar Ali, Mohamed Ahmed, Md Mahfudz Md Zan, Habibah Hashim

Abstract—**Robot-based assistive technologies have in recent times, become an important research topic. Most commercial robots come with control systems which may support several types of user inputs/outputs, but usually provide support for application-specific motion control. In developing high level robot-based assistive application, there is a need for more open scheme for controller design. In this paper, a Raspberry Pi-based controller intended to extend the features of the commercial Bioloid humanoid robot was designed to provide an open-architecture alternative than its proprietary controller, the CM-530. Given that the custom-designed controller is more open and provide greater flexibility to developers, a comparison is also made towards its ability to provide better support in terms of control perspectives. The custom-designed controller provides better capabilities regarding to its open-architecture which gives an opportunity for other developers to delve further into the structure knowledge that helps many aspects of application development. The open characteristics of proposed controller consequently will enhance the controller potential/capabilities and can be utilized by other robots in future. The outcome of the experiments revealed that the open control system provided by the Raspberry Pi platform has slightly higher average power consumption which is 2.04W difference from CM-530 controller during the idle mode of 18 servomotors, but is able to provides better capabilities. As for dynamic servomotors, the average power difference recorded for single servomotor motion is 3.08W and 9.3W for multiple servomotors. All results were calculated and graphed using MATLAB R2015a software.**

***Index Terms*—Bioloid robot, CM-530 controller, Raspberry Pi, AX-12 servomotors, open architecture**

I. INTRODUCTION

Humanoid robot has always been a prominent research in robotics field. They typically possessed physical appearance similar to that of a human; including two arms, two legs, and a head. For examples, NAO[1-2], ASIMO[3], i-CUB[4], and HRP-2[5]. Humanoid robot is most likely capable of operating in human environments with the same skill as humans. Therefore, researchers have developed humanoids for assistive robotics [6], education [7], and rehabilitation [8-10] to facilitate humans' activities.

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Cognitive developmental robotics are essential in these applications, as advancement in information processing systems robots to become perceptive, to be able to learn, make decisions, communicate and take actions [11].

Humanoids require a controller in order for the robots to function. Controller is a hardware device or a software program that manages the flow of data between two entities. In this paper, Bioloid Premium Kit developed by the Korean company ROBOTIS is used as shown in Fig. 1.

The Bioloid Premium Robot Kit is the first robot of its kind built around serially controlled servo technology with 18 degrees of freedom and powered by Dynamixel AX-12A DC servo motors [12]. The robot has 18 Degree of Freedoms (DoFs) and has 3 motors for arms and 6 motors for legs respectively. The robot is 1.7 kg of weight and its height is 39.7 cm, and it is powered by 11.1V, 1500 mAh of Lithium Polymer (Li-Po) battery.

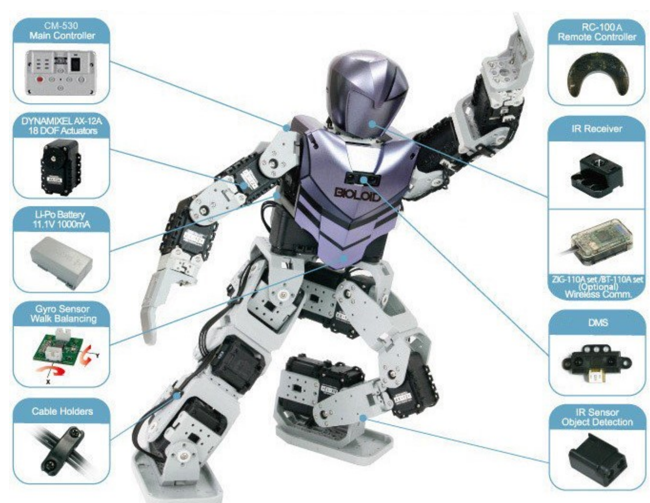


Fig. 1.Bioloid Humanoid Robot Type-A

The original main controller of Bioloid Humanoid Robot is ROBOTIS Bioloid CM-530 controller as illustrated in Fig. 1. However, a new controller to support Dynamixel AX-12 servomotors and other components is proposed in this paper. The controller is developed with an open architecture type in such a way to expose the system design to any inventors who intends to make any further enhancement onto the system, as compared to CM-530. Hence, the humanoid robot can be operated by using one of these two controllers, industrial controller (CM-530) or custom-designed Raspberry Pi-based controller.

In general, any controller has its own system architecture, which can be divided into two classifications; open and close architecture. The system architecture is described as the conceptual model that defines the structure, behavior, and more views of a system [13].

A closed architecture can be defined as a system where the technical specifications and design features of the system are kept proprietary to other manufacturers or developers. Nonetheless, such system allows the company to optimize and control all the elements of the system privately, where the system will have an overall greater performance consequently. On the other hand, non-proprietary architecture allows its specifications to be shared to public as well as provides an open platform where it reveals its own system, subsystems and components as illustrated in Fig. 2. This enables a faster rate of innovations as it provides an opportunity to other developers to make augmentations to the system. In addition, this reduces the ongoing cost of maintaining and supporting the system since the provider does not have to take all the responsibility for each and every component of the system.

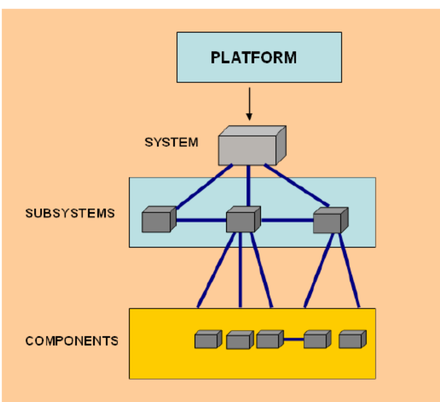


Fig. 2.Illustration of an Open Architecture System

Most of the conventional robotic controllers are designed with closed architecture such as non-standard hardware interface, customized communication protocol and special program language [14]. Referring to the datasheet in [15], ROBOTIS CM-530 is a closed-type as well as the maker does not provide important details on the system structure such as full schematic of the system.

There is a need for developers to have more control over the behaviors of the humanoid robot. If the architecture were made open, this will stretch more capability and flexibility [14] to developers as it provides beyond humanoid functionality without limiting the functions of the manufacturer controller. Thus, such open systems authorize the third party to do their own configurations on the controller.

In order to investigate whether the custom-designed controller has the capabilities substituting the manufacturer controller to support the humanoid robot's motors and modules, a comparative analysis between CM-530 and the designed controller will be carried out in this paper. This includes the analysis of the performance of ROBOTIS humanoid robot during idle and static state, overall functionality of both controllers. The contributions of the work presented in this article are as follows:

1) *Additional Layers for Open Architecture*
   The integration layer has been added onto the architecture to provide an open platform as compared to the original architecture.
2) *Open Circuit Design*
   Schematic of the circuit design of this work is opened to other researchers in order to facilitate the integration with other components and can be made available upon request.
3) *Verification of Open Controller*
   Open controller circuit design is verified through the performance analysis of power consumption.

The next section describes the related works on the previous research. The research methodology is presented in Section III. Then, Section IV describes results and discussion of this research work. Finally the conclusion of the research work is presented in Section V.

II. Related Work

Nowadays, the robotics community have developed their own controllers for humanoid robot, such as paper [16], [17], and [18]. In [16], the author proposed a reflex based neuro-controller for ARMAR-4 humanoid robot. The final results show that reflexive control schemes benefits not only to ARMAR-4, but also to other humanoid robots generally.

The writer in [17] presented a control architecture to achieve push recovery under strong disturbances by using the concept of the Capture Point. The Capture Point is defined as the point on the ground where the foot must be placed in order to stop the mass in the vertical upright position [17]. Simulation results and experiments on the iCub humanoid robots validate the soundness of the proposed approach.

In [18], the researcher substituted the manufacturer controller by developing an open architecture controller for a humanoid robot. They used Rapsberry Pi 2-based controller and BUFFER NOT as linker on the communication between the Raspberry Pi 2 and the humanoid servomotors. Result shows that the proposed controller has several advantages over the manufacturer controller in terms its performance in programmed routines, such as oberserving and walking.

For Bioloid humanoid robot, there are researchers that use the original controller from ROBOTIS company such as CM-5 [19-21], CM-510 [21-22], CM-530 [23-24] and CM-700 [21] controller. For instance, CM-5 controller is programmed in [19] for robotics-based immigration course to be put into the Computer Systems Engineering (CSE) BS degree. [20]'s controller is similar to [19], where the authors use CM-5 as a main controller for a precursor and a proof of concept for the implementation of robot networks.

In [23], CM-530 controller is used for the development of a set of motion models for the humanoid Bioloid for each character in the Spanish alphabet. Same goes with [24] where the authors utilized ROBOTIS CM-530 for biped robot balancing on a planar nonstationary board, and the accelerometer and gyroscope module installed in the robot torso are used for complementary filter for a better stabilization in faster and slower changes of the inclined board.

Based on the reviewed papers in [19-20], [23] and [24], it can be concluded that they are limited to available resources and functions of bioloid as the manufacturer's architecture controller is a proprietary type. Consequently, this prevents the third parties or developers to make any further enhancements nor modifications onto the available system. Nevertheless, there are researchers whom have openly created their own custom-made controller for Bioloid humanoid robot to suit their experimental needs.

This can be seen in [25], where the writers used Arduino Mega replacing industrial controller as a main microcontroller for gesture recognition. IC 74LS241N is used as a gateway for data transmission between Arduino and dynamixel Bioloid Robot as Arduino uses full duplex with 2 data lines whereas dynamixel motors require a half-duplex serial communication which requires only 1 data line for communication. Therefore, IC 74LS241N itself is a serial data multiplexer that helps to communicate with more than one dynamixel motors.

In addition, [26] introduced a method to connect Pixy CMUcam5 as the vision detector of a robot soccer. The author found that it was challenging to study the connection of Pixy CMUcam5 to CM-530 since their camera is low-prized compared with other Bioloid embedded vision camera module, Havimo. Therefore, they decided to have Arduino microcontroller working as the main processor while maintaining CM-530 as a processor of actuators.

Authors in [18] proposed a controller using Raspberry Pi 2 (RPi 2) to perform the control of a humanoid robot on a more efficiently and faster way to achieve a total control of the Dynamixel motors AX-12 and MX-28. The researcher used 74LS244 octal buffers and line drivers with 3–state outputs acts as a communication bridge between RPi 2 and servomotors, which is same as IC 74LS241N as in [25] but with a different connection. [18] presents an openness of its system structure and the circuit connection between RPi 2 based controller and servomotors.

In this research, Raspberry Pi 3 Model B (RPi 3) is used as a proposed controller which has better performance compared to previous study in [13]. Therefore, the proposed controllers' performance is evaluated in terms of power consumed over period of time and compared to the controller in CM-530.

III. Methodology

The research starts with studying the workflow of humanoid robot's operation in order to have a comprehensive understanding on how the full system works as illustrated in Fig. 3.

The first stage involves RoboPlus software that aids uploading the file motion of Bioloid robot to the main controller. As for the second stage, CM-530 controller controls all the humanoid robot functionality such as sensors and 18 units of AX-12 motors. The last stage is the software and hardware implementation on ROBOTIS humanoid robot Type-A by performing the desired modules.

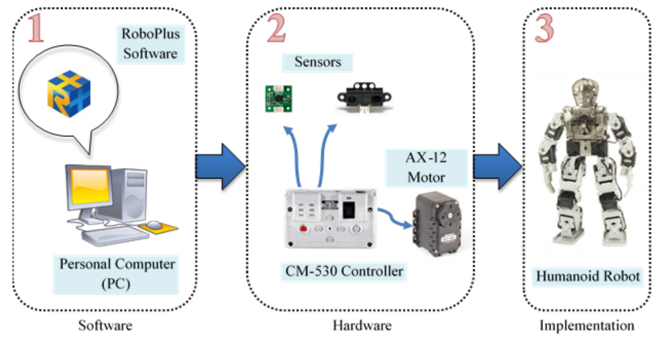


Fig. 3.Operation Workflow of Bioloid Humanoid Robot

A. *ROBOTIS CM-530 Controller*

Next, the research continues with in depth study of software and hardware of original controller of Bioloid Humanoid Robot Type-A (CM-530). This aids to acquire the best review on designing the proposed controller for the humanoid robot. RoboPlus version 1.0 is a free software that allows interface with all of ROBOTIS' hardware, including ROBOTIS CM-530 controllers, Dynamixels AX-12 motors and other hardware components. The software allows you to upload the desired humanoid's file motion to the ROBOTIS controller via USB cable. In [15], the controller's hardware contains several important technical parameters as listed in the Table I below:

TABLE I
CM-530 Parameter

Parameter	CM-530 Controller
Nominal Input Voltage	6v – 12V
Maximum Output Current	10A
IDLE Current	50mA
Wireless Communication	ZIGBee Bluetooth
Hardware Components	Dynamixel AX-12 Motors, Gyro Sensor, IR Reciever, Distance Measurement Sensor (DMS), IR Sensor Object Detection
SoC	STM32F103RE

The CM 530 limits the capability to use external sensors other than those provided by manufacturer. But our proposed controller has access to all built in sensors of the bioloid robot as well as to external third party components and sensors through the provison of the Integration Layer.

B. *Proposed RPi 3 Controller*

Then, a new controller is proposed using Raspberry Pi 3 Model B that uses quad core 1.2GHz Broadcom BCM2837 64bit CPU according to [27]. It is made an open architecture type compared to the manufacturer controller, where the system is made proprietary. The controller's board is designed by using Altium Designer Summer 09 software. There are three layers in the controller's system architecture; Task Layer, Integration Layer and Physical Layer, as indicated in Fig 5.

In the Task Layer, humanoid's controller is remotely accessed by a personal computer via Secure Socket Shell (SSH) connection where RPi 3 is allowed to search, install and download libraries from a computer. For the Integration Layer, the proposed controller is integrated with other components. Lastly, the Physical Layer, where this layer is the completion of the system and Biolod robot accomplished the required tasks given by the commands. RPi 3 controller is remotely accessed from user's personal computer Secure Shell (SSH) connection.

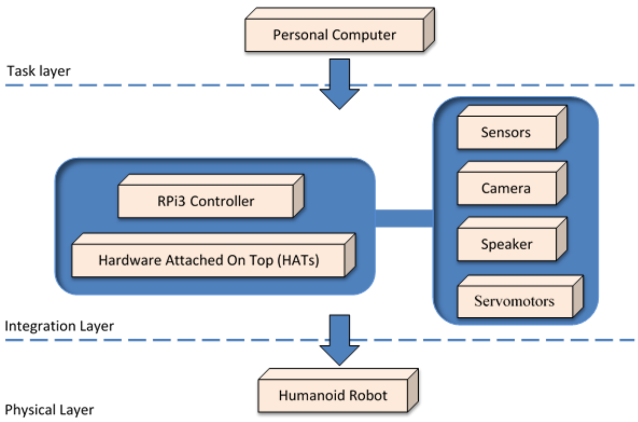


Fig. 4.Architecture Layers of Proposed Controller

Afterwards, the RPi 3 controller is tested on humanoid robot to verify its functionality. All AX-12 servomotors' velocities are calculated using equation 1 which was formulated for the new controller.

$$\bar{\omega} = \frac{\Delta\theta}{t} \qquad (1)$$

where,

$\bar{\omega}$ = angular velocity, rad/s

$\Delta\theta$ = angle (angular position), rad

t = time, s

The equation 1 is translated into Python language as shown in Fig. 5.

```
def CalcSpd(self,initPOS,POSdesired):
    for k in range (0,18):
        disPOS[k-1]=(initPOS[k-1])-(POSdesired[k-1])
        disPOS[k-1]=abs(disPOS[k-1])
        spdcal[k-1]=int((disPOS[k-1])/time)
    return spdcal
```

Fig. 5.Snippet of Coding for Angular Velocity Equation

Next, the experiment is conducted through humanoid robot operation, In idle and dynamic modes, by applying manufacturer and custom-designed controllers on Bioloid robot as can be seen in Fig. 7. This experiment extracts voltage and current value to calculate the power consumption for robot controllers. Bioloid Humanoid Robot Type-A created by Korean company (ROBOTIS) as the main subject, whereas 1000mAh 10C Li-Po battery supplies power to the servomotors and other hardware components. The main components used in this experiment are Arduino Nano microcontroller, B25 voltage sensor module and 30A ACS712 current sensor module. The experimental flow is summarized as in Fig. 6.

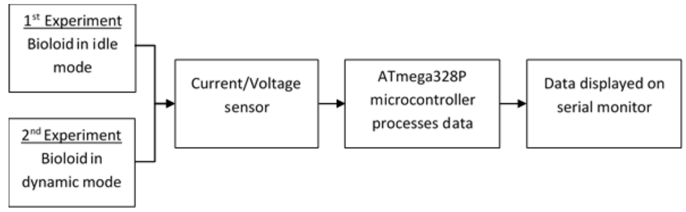
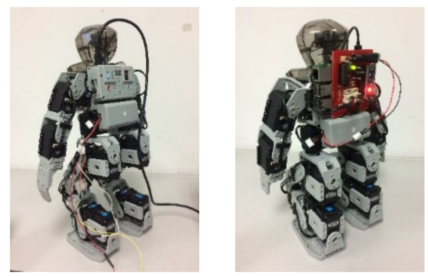


Fig. 6.Experimental Flow



(a) (b)

Fig. 7. (a) CM-530 and (b) Custom-Designed Raspberry Pi-Based Controller on Bioloid Humanoid Robot

In all experiments, measurements are obtained from current (ACS712T ELC-05B)/voltage sensor systems and verified by a multimeter as shown in Fig. 8.

In the initial experiment, all of 18 units of Bioloid robot servomotors are put in idle mode. This mode is tested under two conditions; when it's linked and not linked to the main controller. This helps to calculate the value of power drawn from the Li-Po battery to the main controller. Both controllers are tested by continuously on the battery while the robot is not operating to measure time taken for Li-Po battery to run out. This can be done by charging humanoid's Li-Po battery using 2S Lithium Battery Charger until it is fully-charged and run the stopwatch as soon as the the battery connects to the controller.

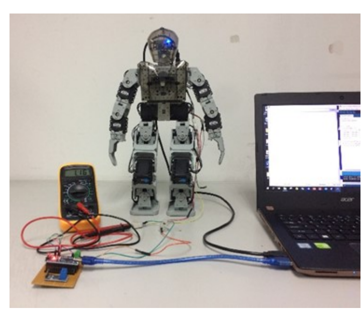


Fig. 8.Experimental Set-Up

As for the dynamic mode, where the servomotors are in motion, the trial will run either on single and multiple Dynamixel AX-12 servomotors. First, only one of 18 units of servomotors will be tested its power consumption and afterwards Bioloid robot will execute a motion, which is bow motion lasting for 20 seconds. During the bow motion, there are

3 motions are involved which are stand up position to bow motion and back to stand up position.

Lastly, both controllers' average power consumption are calculated and illustrated using MATLAB R2015a software and both controllers capabilities will be evaluated in order to determine its competency for Bioloid humanoid robot.

IV. Result and Discussion

A. Bioloid Operation in Idle Mode

1) Voltage

Both controllers voltage is around 12.54V when the Li-Po battery is not connected however the voltage slightly changed when the battery is connected to the controller.

TABLE II
No Load Voltage and Connected Load Voltage

Types of Controller	No Load Voltage (V)	Connected Load Voltage (V)
CM-530	12.54	12.53
RPi 3	12.54	12.44

Referring to Table II, the Raspberry Pi controller caused a 0.1V drop while the battery's voltage drop slightly by 0.01V when the CM-530 was connected to the Li-Po battery.

2) Power Consumption

The overall power during idle mode can be calculated using the equation 2:

$$P = V \times I = \frac{V^2}{R} = R \times I^2 \quad \text{———} \quad (2)$$

where,
P = power, W
I = current, A
V = voltage, V

TABLE III
Power in Idle Mode

Types of Controller	Voltage (V)	Current (A)	Power (W)
CM-530	12.53	0.71	8.90
RPi 3	12.44	0.88	10.94

The power difference in Table III occurred because RPi 3 consumes higher idle current compared to CM-530, which is 300mA and 50mA respectively. Besides, RPi 3 itself is a Broadcom BCM2837, which is ten times the performance of its first generation, Raspberry Pi 1 as stated in [27] and [28]. Therefore, this contributes more to the voltage decrement.

3) Total Amount of Time for Battery to Drain

Next, the time in minutes of Li-Po battery to run out is taken using a manual clock while Bioloid robot is in sitting position as illustrated in Fig. 7 (b). The initial voltage and final voltage of the battery were also measured. Both controllers used the same Li-Po battery.

TABLE IV
Time Taken for Battery to Drain

Types of Controller	Initial Voltage (V)	Time (Minutes)	Final Voltage (V)
CM-530	12.53	~84	0.002V
RPi 3	12.44	~80	0.020V

CM-530 controller's battery was able to last around 86 minutes while for the RPi 3 controller lasted around 80 minutes as shown in Table IV. Nevertheless, the difference in battery life between the two controllers can be considered quite insignificant as the RPi 3 controller lasted 4 minutes less than CM-530 controller's battery.

B. Bioloid Operation in Dynamic Mode

In dynamic state, humanoid robot will create a motion using the AX-12 servomotors, where this operation falls into two categories. The first one is Bioloid robot operation using a single motor moving from minimum angle to its maximum angle. Secondly, a simple action of Bioloid Robot involving multiple action of servomotors will be carried out. The measurements of voltage, current and power were recorded over a duration of 20 seconds. All results were calculated and graphed using MATLAB R2015a software.

1) Single Servomotor

Servomotor ID 6 was selected among of all 18 units of servomotors as it has an adequate area to move about. The minimum angle is 0 in analog value while the maximum angle is 1023 in analog value. The servomotor starts moving from 0 analog value at 9th second and 1023 analog value at 20th second.

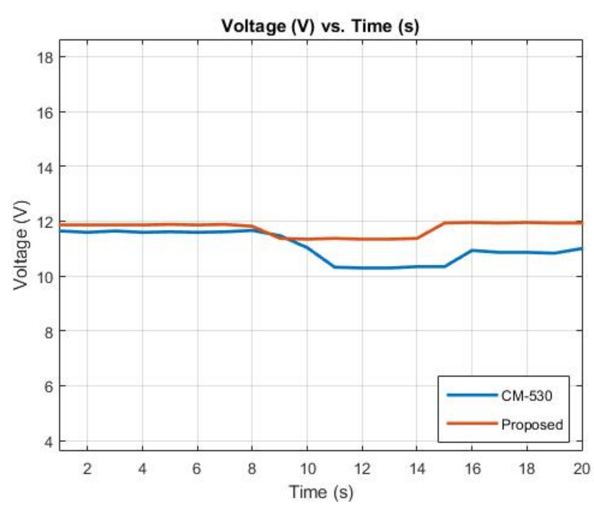


Fig. 9.Voltage (V) vs. Time (s) for Single Servomotor

Based on Fig. 9, the voltage of RPi 3 controller is slightly higher than ROBOTIS's controller. However, the time taken for Bioloid to perform motion ends earlier, which is at 15th second compared with CM-530's, 16th second.

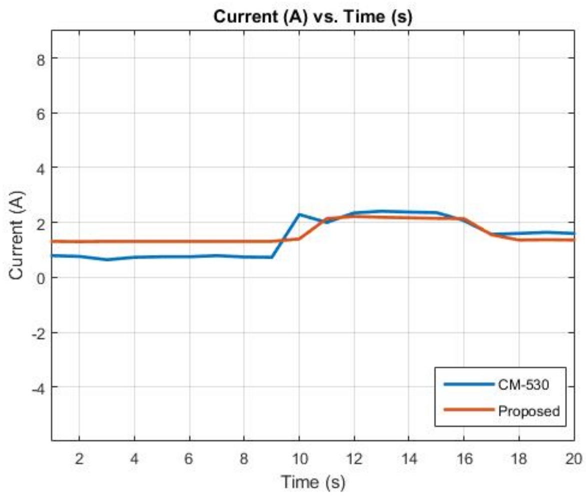


Fig. 10.Current (A) vs. Time (s) for Single Servomotor

In terms of current consumption, CM-530 consumed a lesser amount of current than the RPi 3 controller as presented in Fig. 10. The graph of the RPi 3 controller is more steady and does not change drastically as the manufacturer's.

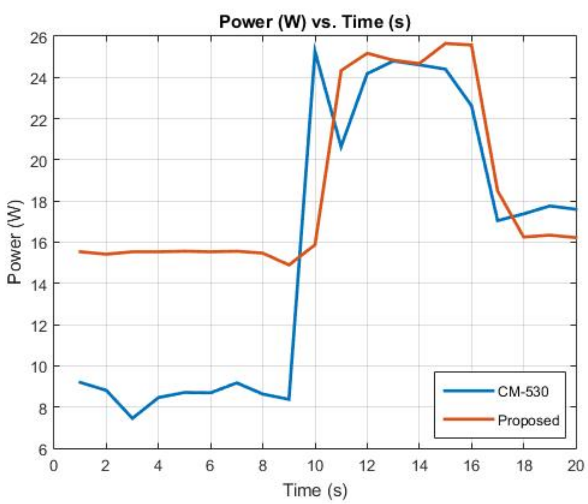


Fig. 11.Power (W) vs. Time (s) for Single Servomotor

Fig. 11 shows the RPi 3 controller's power consumption is 1.6 times higher than CM-530 between 1th second to 9th second. However, both controllers' power consumption shows the same pattern starting from 10th second to 20th second. Power consumption for both controllers is calculated using equation 2. The power consumption of the proposed controller is higher at the intial point but consumed almost the same power with CM-530's between 9th second to 20th second when the ID servomotor 6 moved from 0 to 1023 analog value.

Afterwards, the average power was calculated by referring to the equation 3. Table V shows the average power consumption throughout the motion.

$$P(avg) = \frac{P_1 + P_2 + P_3 + ... + P_n}{T} \qquad (3)$$

where,

$P(avg)$ = average power, W

$P_1 + P_2 + P_3 + ... + P_n$ = total power, W

T = total time, s

TABLE V
AVERAGE POWER OF SINGLE SERVOMOTORS

Types of Controller	Average Power (W)
CM-530	15.54
RPi 3	18.62

Referring to Table V, the average power difference for single servomotor between the two controllers is 3.08W.

2) Multiple Servomotor

The motion selected for this category is one that starts with the robot standing position as it completes a simple bow motion within 20 seconds time duration, demonstrated by Fig. 12.

Fig. 12.Bioloid Performs Bow Motion

Fig. 13 shows voltage of both controllers for a bow motion within 20 seconds. The bow motion starts from 9th seconds and ends at 18th second. The voltage of the proposed controller dropped from 9th second to 10th second while ROBOTIS's CM-530 has a steady voltage througout the 20 seconds.

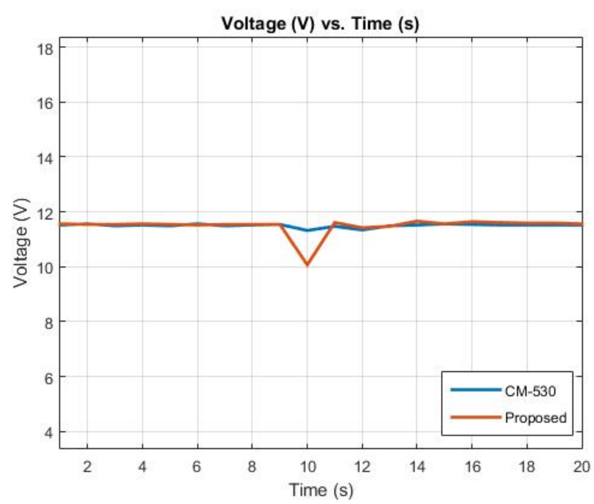


Fig. 13.Voltage (V) vs. Time (s) for Multiple Servomotors

The current consumption of manufacturer is lower than custom-designed controller's as graphed in Fig 14. The current of RPi 3 controller is slightly fluctuated in contrast to CM-530's.

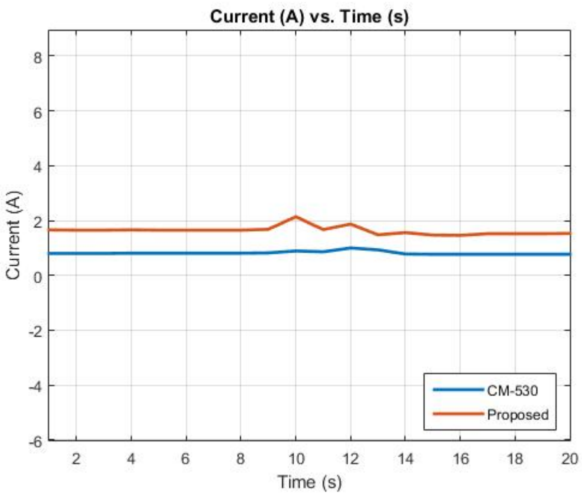


Fig. 14.Current (A) vs. Time (s) for Multiple Servomotors

Power consumption is measured by using MATLAB R2015a software as graphed in Fig. 15. Both controllers power consumption for each second that was calculated from the previous equation 2.

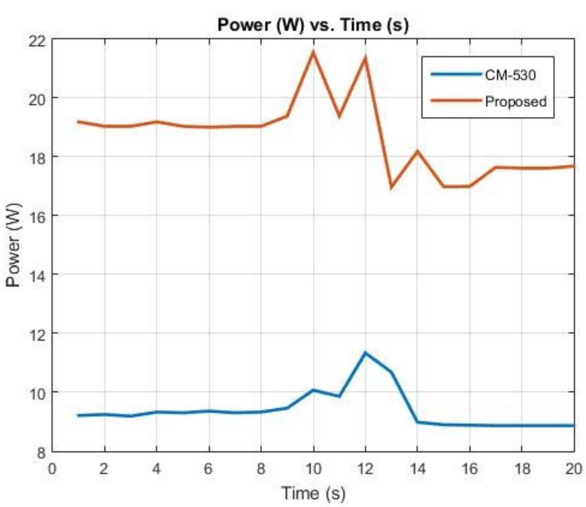


Fig. 15.Power (W) vs. Time (s)

Next, the average power for both controller was calculated by referring from the previous equation (2). The result shows that the average power of manufacturer controller consumed less than the custom-designed controller by 9.3W as depicts in Table VI.

TABLE VI
AVERAGE POWER OF MULTIPLE SERVOMOTORS

Types of Controller	Average Power (W)
CM-530	9.40
RPi 3	18.70

To summarise, the RPi 3 controller consumed high power consumption due to its architecture requiring a Linux operating system (OS) according to the datasheet in [27]. Meanwhile, CM-530 controller acts as a microcontroller as shown in [15] and does not run any operating system. Furthermore, the performance of the Pi 3 is roughly 50-60% faster than the Pi 2 which means it is ten times faster than the original Pi according to Element 14 in [27] and RS Components in [28]. In general, microprocessors has no power saving system and also many external components are used with it therefore this has led to high power consumption in comparison with microcontrollers.

C. Controller Features

In support of cognitive developmental robotics, the open architecture of our RPi 3 controller has enhanced the controller potential and capabilities while giving more advantage to application developers. Referring to both controllers technical specification in [15], [27], and [28], CM-530 and proposed controller were compared based on the characteristics of humanoid robot features that are listed in the following Table VII.

TABLE VII
CONTROLLER FEATURES

Bioloid Controller Features	CM-530	RPi 3
Components integration	IR Sensor, Gyro Sensor, Voltage Sensor, Sound Sensor, DMS Sensor, Touch Sensor	Open to all Raspberry-based sensors and actuators
Wireless communication	Bluetooth 4.0, Zigbee, IR Receiver	Bluetooth 4.1, Wi-Fi, LoRaWAN etc .
Modification from the third party	Not allowed	Allowed
Originality of the controller	Yes	No
Full control of the system privately	Yes	No
Maintainance cost	High	Low
Power consumption	Low	High
Delay	Low	High
Operating system	No	Yes

Referring to Table VII, integration of components to CM-530 controller is limited to the number of manufacture's sensor modules as compared to the proposed controller. The reason is that ROBOTIS' closed-system controller is incapable of receiving any installations nor modifications of new components from the third party whereas the open-architecture of the proposed controller have the potential to receive them. Consequently, the RPi 3-based controller able to facilitate the exploration of humanoid robotics on an open architecture hardware and software while the CM-530 controller maintains its system structure as the manufacturer has the have a full control over the system specifications and functionalities. Therefore, the maintaince cost of CM-530 controller is high for the user as the user is required to send back to the manufacturer whenever there was a faulty.

The advantage of having operating system (OS) is that it supports many types of applications and software repositories. In the case of the proposed RPi 3 controller, an open source OS is used whereby developers will have access to a great number of open source codes. As a result, this leads to a rapid innovation as well as lower cost of innovation and system development.

V. Conclusion and Future Work

In conclusion, it has been proven that ROBOTIS CM-530 controller is advantageous than the proposed Raspberry Pi-based controller for bioloid humanoid robot in terms of its average power consumption of Bioloid operation during in idle and dynamic modes of servomotors.

It also can be concluded that the manufacturer's controller capabilities is beneficial in terms of originality of the controller, privately owned the system and lower power consumption. Nevertheless, the cost of the maintainance is high due to the closed-architecure of CM-530 controller as compared to the openness characteristics of the proposed controller that enables the third party to study further into the system structure.

This eventually helps developers to deploy any further developments and augmentations onto this recent custom-designed controller system which consequently will correspond with the manufacturer's controller that benefits for application development areas of education and rehabilitation in future.

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