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作品名稱 A Humanoid Robot on the Basis of Modules Controlled Through a Serial Half-Duplex UART Bus

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關鍵詞 humanoid robot, bipedal walking robot, intelligent servomotor, ESP32, ecosystem of modules

作者照片

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on the Basis of Modules Controlled Through
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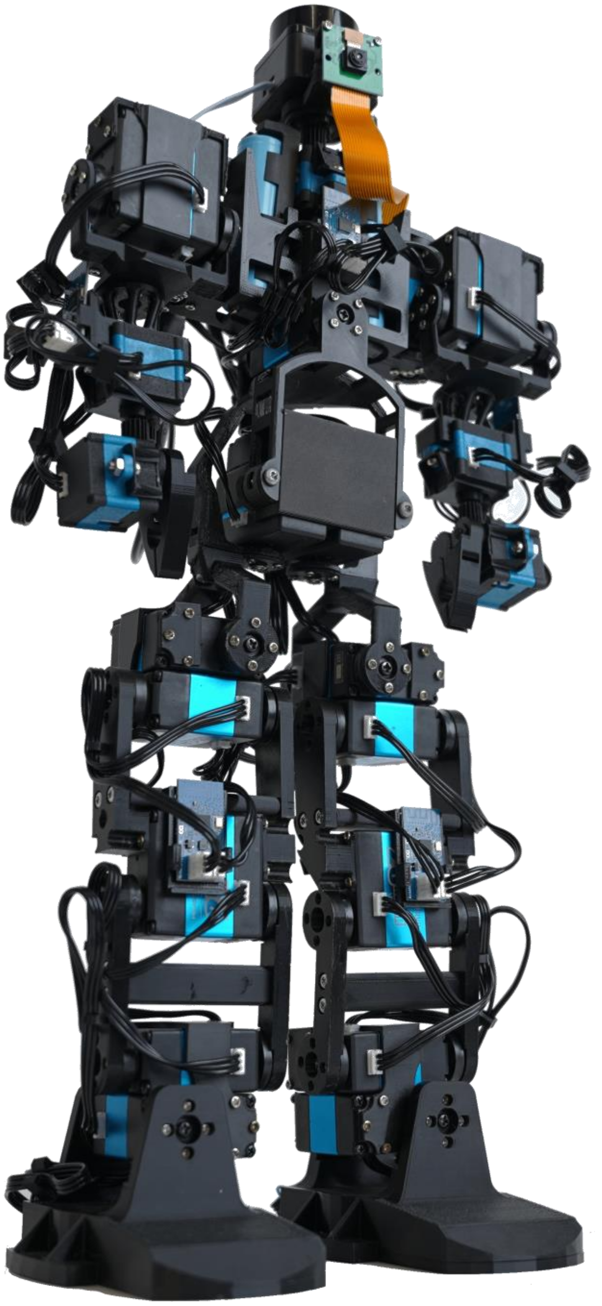

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Czech Republic 2024

Abstract

This thesis presents the design and construction of a small-scale humanoid robot, covering all aspects from 3D modeling to electronics design and programming. The robot is built entirely from custom 3D-printed components, with a new servomotor developed specifically to meet the project's requirements. During the robot's development, custom electronics were also designed, leading to a modular platform that enables easy interaction with diverse modules like servomotors and inertial measurement unit (IMU) modules. This modular approach allows these components to be programmed and controlled with minimal adjustments, as well as making development of potential future modules straightforward. The robot is operated via a computer application that includes a graphical user interface for displaying real-time data from the robot.

Keywords

humanoid robot, bipedal walking robot, intelligent servomotor, ESP32, ecosystem of modules

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Introduction

Just a few decades ago the concept of humanoid robots assisting us at work would be something better suited for a movie plot than as a business plan. However, nowadays tests of such robots are already ongoing and widespread, with big companies exploring the possibilities of such robots working in warehouses, directing lost passengers at the airport or playing the role of personal assistants. In the future, such robots could very well be employed in many more areas of work - thanks to their construction being similar to humans, they integrate well into our everyday environment and make cooperation more intuitive.

In this project, a small-scale version of a humanoid robot was designed and assembled. First, the legs of the robots were designed and an initial version of the robot was constructed. However, during the initial design and assembly phase, issues with store-bought servomotors were encountered. The microcontroller embedded within the servomotors could not be reprogrammed, limiting the ability to customize their functions or motion profiles. Additionally, the abrupt start and stop of these servomotors posed challenges. Finally, there was the necessity of smaller servomotors for building the robots upper limbs (which would need to be programmed differently, considering the difference in hardware). Therefore, it was decided that custom electronics for the robot's servomotors would be made.

This concept of creating custom servomotor electronics led to the design of a whole ecosystem consisting of different modules, all with shared key features - the same microcontroller, all controlled through half-duplex UART, and even with most of the program being the same. Going forward, the robot evolved from a single central computer controlling individual motors to more of an interconnected network with individual modules all working together to deliver the wanted result - to walk.

Project Goals

The main objective of this project was to create a scaled down humanoid robot capable of walking on two legs. A more detailed enumeration of the goals is as follows:

- Two legs built using servomotors to walk
- Two arms proportional to the legs able to grip light objects
- Custom electronics for effective operation and control
- The ability to recharge accumulators without disconnecting them from the robot
- A computer application to monitor and control the robot

Initially, the robot was only supposed to feature two legs, and only throughout the project was it decided that the robot should have arms and a head as well. Due to this, the mechanics chapters will briefly touch upon the initial version of the robot which had only legs, and then focus on the complete humanoid robot.

Mechanics

The development of mechanics was the first step towards creating the humanoid robot. Starting from the design of the legs, the robot was basically built from the foot soles upwards. The robot's parts were 3D modeled and then printed, with the assembly shortly following.

Servomotor Selection

The plan was to utilize servomotors to move the robot, and due to the number of servomotors used it was essential to find a way to power and control them with as few components as possible, to keep the whole robot compact.

Following through with this reasoning, servomotors controlled through a serial bus (half-duplex UART) were used. The LX-225 (see Fig. 1) is the servomotor that mainly powers the robot. It has a movement range of 270° divided into 1000 steps, and is also capable of position and voltage feedback, among other features. It was purchased online, but afterwards the electronics were replaced to allow for reprogramming. For the arms of the robot, smaller servomotors were necessary, but not finding such small form-factor serial bus controlled servomotors on the market led to designing them custom, and utilizing the same electronics which were put in the LX-225 servomotors.

Fig. 1 LX-225

Custom Servomotor Design

To be able to build arms that would be proportional to the legs, it was crucial to develop new, smaller servomotors. Using the motor, gears and potentiometer from an MG-90 servomotor, and custom electronics created for the LX-225 servomotors (more on that in the chapter Electronics), I was able to create a servomotor controlled through a serial bus, with a form factor of about 25x25x30 mm compared to the 20x40x55 mm of the LX-225. An exploded view of the custom MG-90I servomotor is shown in Fig. 2.

Fig. 2 MG-90I servomotor exploded view

Mechanical Design of the Robot

Since the initial objective was to create just the legs of the robot, the first design consisted of 13 servomotors which made up the legs and torso (the torso carried the batteries and electronics). Building upon this design, with minor changes to some of the parts, the robot's arms were designed as well. There are 22 servomotors in the final design, 17 of which are the purchased LX-225 and 5 are my custom MG-90I. The 3D model, created in Solidworks, can be seen in Fig. 3.

The arm assembly utilized two of both types of servomotors, where the LX-225 servos serve as the arm joint and the MG-90I servomotors as the wrist and gripper. The assembly is shown in Fig. 4.

Fig. 3 3D Model of the completed robot

Fig. 4 3D model of the arm assembly

Electronics

The robot is run by the Raspberry Pi Zero 2W single-board computer, but requires further electronics to power and communicate with the servomotors and charge the accumulators.

Custom electronics were initially only meant to be designed for powering the robot, but due to the inability to reprogram the purchased servomotors (for example, a smooth start-up and ending was not possible to implement) and the necessity to create smaller servomotors, custom electronics were also designed for this purpose. Following the design of custom PCBs for servomotors, I also designed electronics that had onboard an Inertial Measurement Unit (IMU), which fit into the existing half-duplex UART serial bus environment.

The complete schematics can be viewed in the chapter Attachments.

Main PCB for Power Management

As the name already suggests, this PCB was designed to power the robot. It was designed as a Hardware Attached on Top (HAT) board for the RPi Zero 2W, and powers both the computer as well as the servomotors, while also allowing to charge the accumulators, and converts the full-duplex UART communication from the RPi Zero 2W into half-duplex UART for the servomotors, and vice versa.

Power Management

The robot is powered using two 18650 Li-Ion cells connected in parallel, but the servomotors require a supply voltage of about 8.6 V. This meant that a step-up regulator design was necessary. The TPS61288 regulator was used, and along with the design shown in Fig. 5 it is capable of sustaining 8.6 V at a steady current of about 6.2 A.

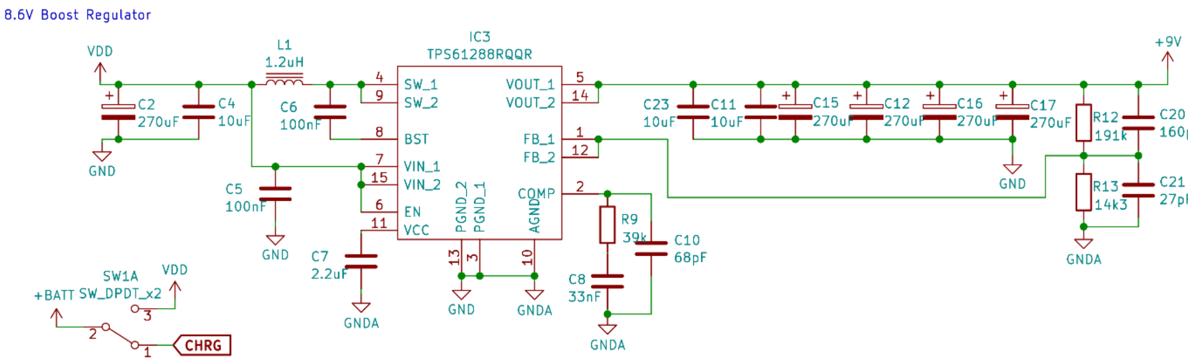

Fig. 5 Schematic of the Regulator for Powering the Servomotors

A regulator for 5 V was also designed to power the RPi, and a charging circuit for the accumulators was created using the TP4056 Integrated Circuit (IC). The robot can be charged through a USB-C connector on the PCB, but it also has wireless charging coils built into his foot soles, which allow to charge him wirelessly using a charging mat. To eliminate superfluous cables, the same cables used to power the servomotors are used (the robot needs to be turned off for charging). To achieve separation from the power regulator when the robot is turned on, the circuit shown in Fig. 6 is used. Q1 is opened with a voltage that is supplied from the accumulators when the on/off switch on the robot is flipped (see SW1A in Fig. 5).

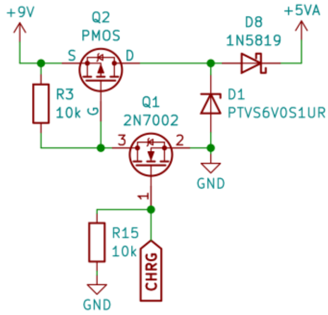

Fig. 6 Charging Circuit and Power Regulator Separation

Communication with the Modules

To convert full-duplex and half-duplex UART for two-way communication, an open-drain buffer was used in the circuit shown in Fig. 7.

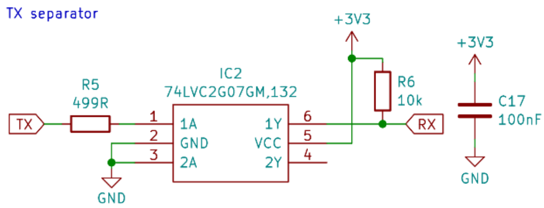

Fig. 7 Circuit for full-duplex to half-duplex conversion

The fabricated PCB for Power Management can be seen in Fig. 8.

Fig. 8 PCB for Power Management

Custom Servomotor PCB

As was already noted, this PCB was created for two main reasons – to allow to add functions to the LX-225 servomotor, and to have a one-PCB-fits-all solution for the new MG-90I servomotor as well.

The PCB is based around the ESP32-C3FH4, which has internal flash storage, meaning it is not necessary to add an external IC and thus it's more space efficient. It can also be programmed directly without need for a USB<=>UART convertor IC, which again saves space.

The motor is controlled through a H-bridge which is constructed using two dual channel WSP4606A MOSFETs. I also added the option to read current through the motor using the INA181 IC, as is shown in Fig. 9.

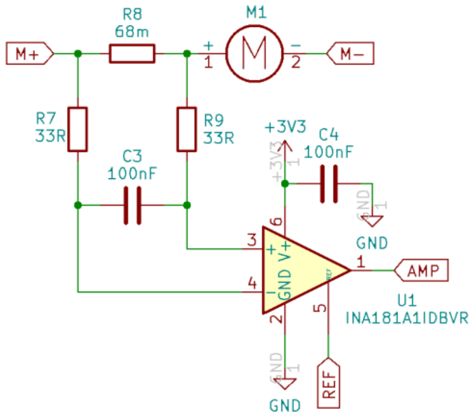

Fig. 9 Current Monitoring using INA181

Additionally, since the ESP32-C3FH4 also uses full-duplex UART, the open-drain buffer used for the Raspberry Pi Zero 2W is also used on this side of the communication. It is therefore appropriate to ask, why not just use full-duplex UART (or even better, a more fitting type of communication as CAN bus) for the whole robot. This decision stems from the fact that the aluminum body of the LX-225 servomotors has a milled opening from a 3-pin connector, and a 4-pin connector would not fit, or an entirely different connector would have to be used, and therefore I stuck with half-duplex UART. Given that the speed of communication can now be changed (previously, it was fixed at 115200 baud), it can be sped up this way, minimizing the inconvenience of half-duplex UART (which is that only one device can communicate at a time).

The completed servomotor PCB model can be seen in Fig. 10.

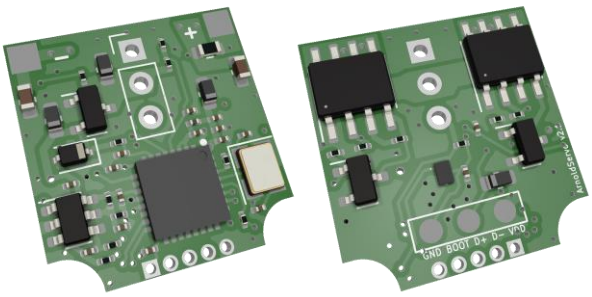

Fig. 10 Servomotor PCB Front and Rear Side

IMU PCB

The impulse to design another PCB which would follow the same characteristics of the servomotor PCB came from the idea to use machine learning to improve the robot's gait. To be able to control the module in a fashion similar to the servomotor, the ESP-32 and overall similar design was used for this board. It is thus possible to use the same program for the module, and upload it only with minor changes, and also the same communication protocol.

The IMU on this board is the LSM6DS3TR-C, which is a 6-axis IMU communicating via I^2C. Simply for practice, I also added a PCB antenna, the SWRA117. It allows to utilize the ESP-32s inbuilt Wi-Fi and Bluetooth capabilities. There are 7 modules of this type placed on the robot. A model of the IMU PCB is shown in Fig. 11.

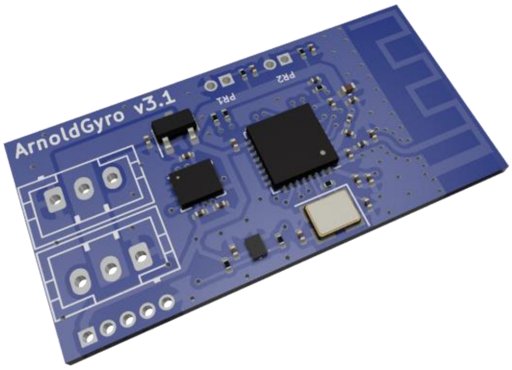

Fig. 11 IMU PCB Model

Miscellaneous

The robot also has a camera and a LiDAR sensor attached to its head, which send the data stream to the computer app and in the future could be used as data for machine learning to improve the robot.

There are pressure sensors in the robot's foot soles and grippers to sense if the robot is gripping something and if the foot is placed on the ground.

Both foot soles have charging coils inbuilt in them for wireless charging as already mentioned with the charging circuit.

Programming

The programming was split into two main sections, with one being the program of the robot and the second the control application. Programming the robot was then divided further into the program for the modules (servomotors and IMU PCBs) and the program for the Raspberry Pi Zero 2W.

Programming the Robot

The modules all use one program, which includes all methods for both the servomotor types and the IMU board, and only the appropriate functionalities are enabled in the different types. The program is written in C++.

The RPi Zero 2W runs raspbian, and is controlled through SSH. The program for the robot itself is written in python and has to be manually executed through the terminal upon the robot's startup.

The Control Application

This app runs on a windows computer and both receives information from the robot to display, and sends commands back. It can be used to execute movements of the robot, and to train the robot. It is written in C#.

Below is a list enumerating the capabilities of the app:

- Displays the current state of the robot – including a 3D model of how the robot's servomotors are angled
- Displays the camera and LiDAR stream
- Graphs the data sent from the accelerometer on the robot.
- Acts as a programming interface for teaching the robot movements

The front page of the app can be seen in Fig. 12.

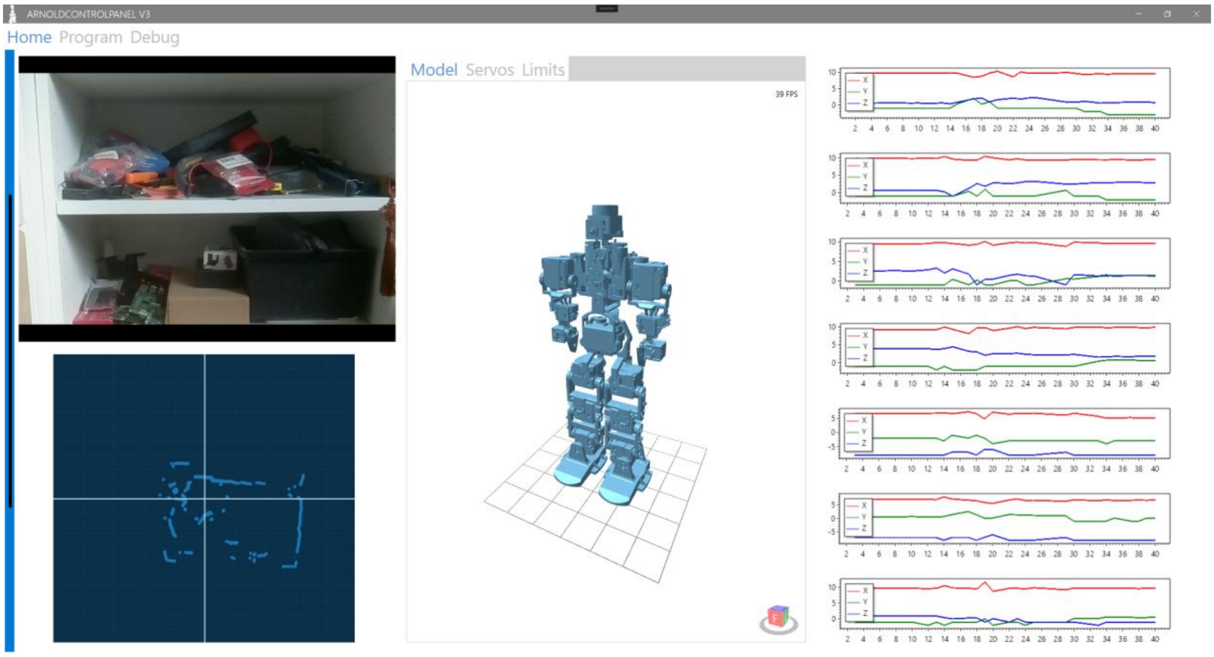

Fig. 12 Control Application

Project Results

The final robot is about 45 cm tall. Consisting of 22 servomotors, five of which are custom made, and weighing in at almost 2 kg, the robot is capable of walking, and also of gripping light objects. It is portrayed in Fig. 13.

The electronics developed for the robot allowed for functionalities to be added - such as charging through the power cables of the modules with only low losses and monitoring motor current, faster communication speed and more. The ecosystem is also completely modifiable, a big and important difference compared to the pre-programmed bought servomotors.

The robot is controlled through a comprehensive computer application which displays all necessary information and makes teaching the robot movements straightforward.

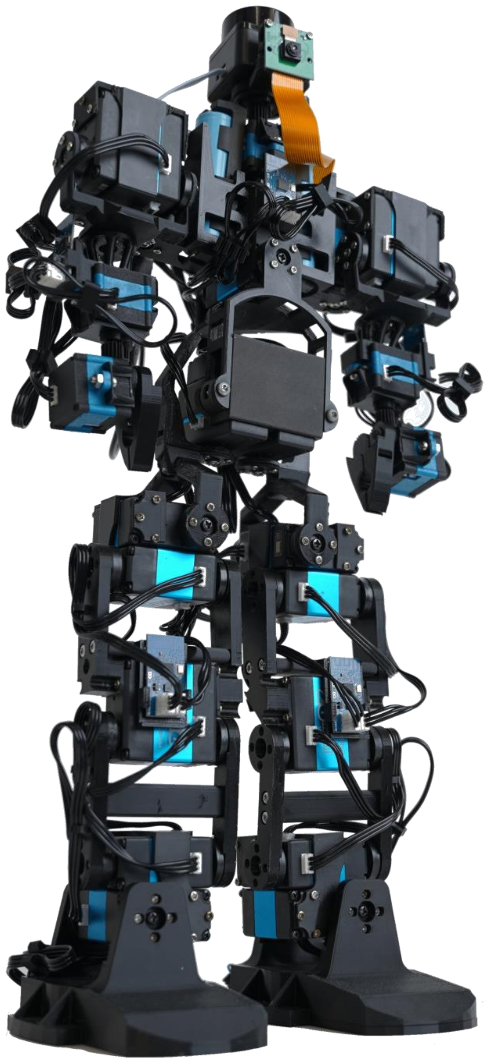

Fig. 13 The Completed Robot

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Attachments

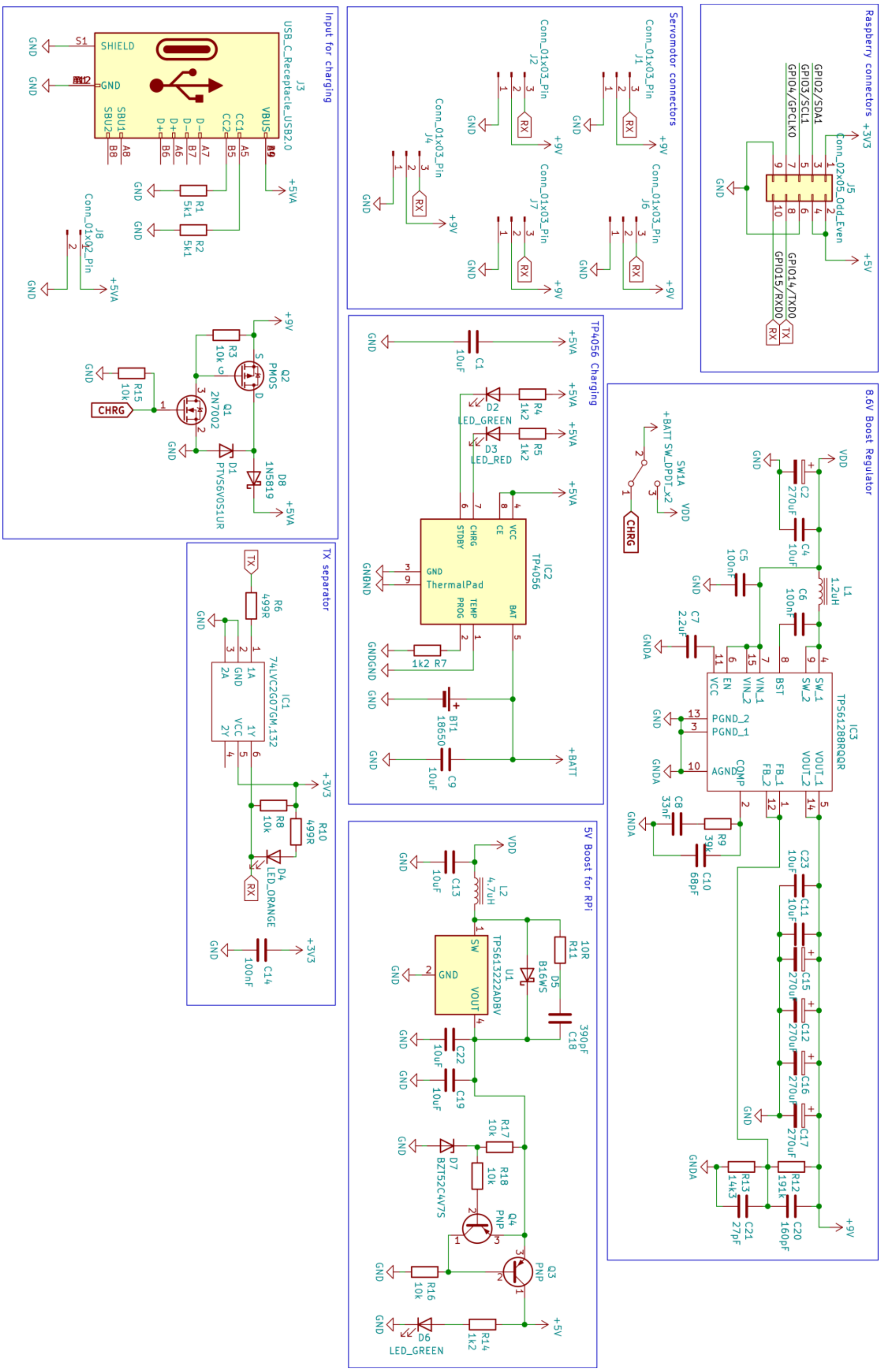

Fig. 14 Power Regulation PCB Schematic

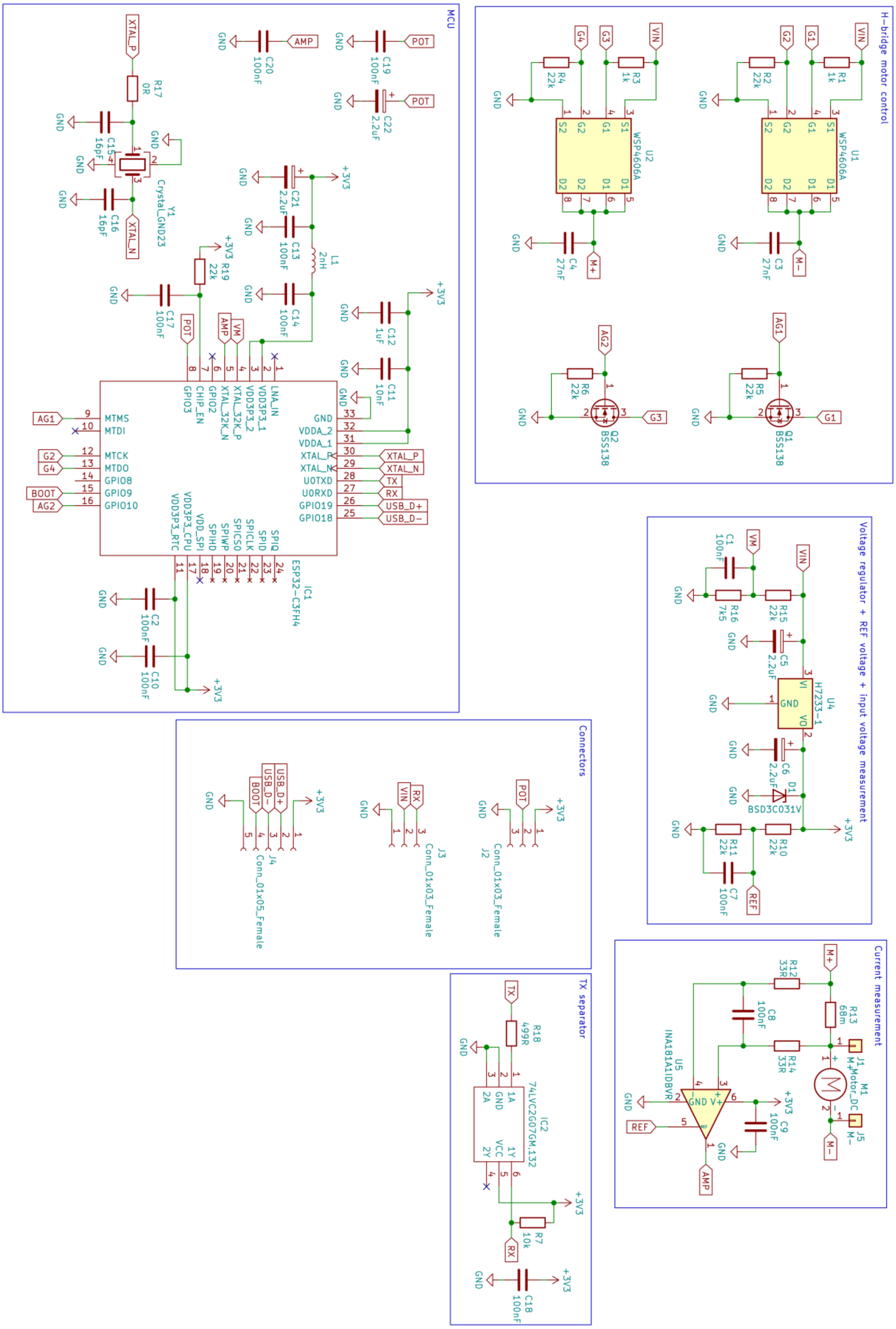

Fig. 15 Servomotor PCB Schematic

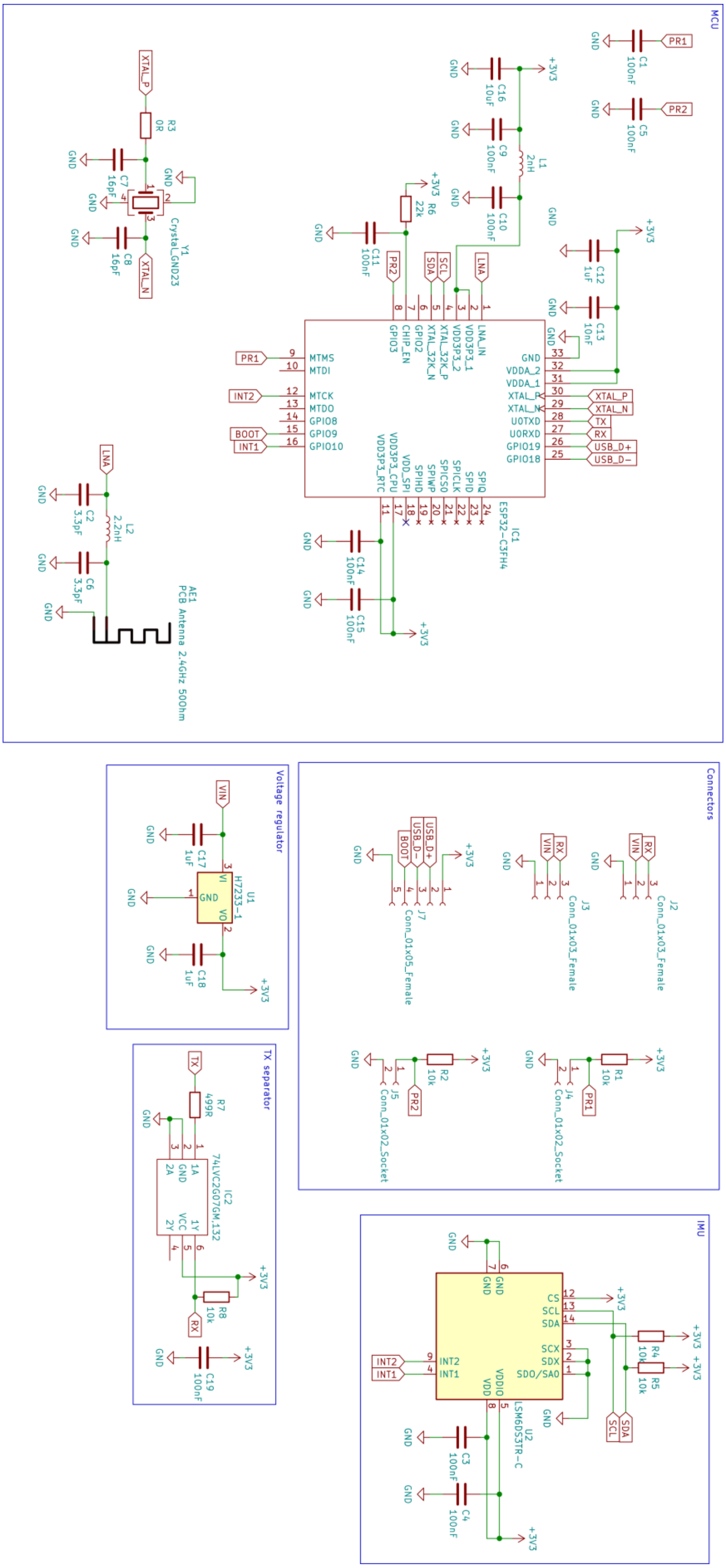

Fig. 16 IMU PCB Schematic

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1. The research topic matches the recent technology buzz for humanoids.
2. In addition to describing the engineering process of this research work, it would be good (also required) to present the innovation of this work. A comparison of the proposed system with existing state-of-the-art methods should be provided in the introduction so the advances, contributions, and novelty of the approach can be identified. (For example, other communication architecture)
3. The project covers mechanical design, mechatronics, and system integration, which I believe takes a lot of effort. In addition to these tasks, performing experimental tests to validate the whole work would be good (and essential).
4. Investigating the extensibility of the approach is suggested.
5. Some other technical questions: (a) Although the current RC servo with metallic frame currently uses 3-pin connectors, the authors can switch to a smaller 4-pin ribbon connector for full-duplex communication. (b) The demonstration of the robot appears to be slow and subject to stability issues.