Personal Research Topics

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***Abstract*—In this paper, the author's experiences of conducting researches in robotics would be mainly described with details in the following sections. Three robots would be mainly discussed. The wheeled mobile robot named *Ares* was designed for the FMB competition, the first robot combat competition championship series held in China. The second one is *Jet-HR1*, a humanoid robot innovatively utilized the ducted-fan propulsion system for balancing the gravitational moment to accomplish large obstacle-crossing. Based on previous research, then the 12 DoFs jet-powered flying humanoid robot *Jet-HR2* (Undergoing) was purposed to have the capacity of flight, contact locomotion, and manipulation.**

I. Wheeled Mobile Robot Ares

Named "Ares", the wheeled mobile robot was designed for the 2017 FMB, China's first robot fighting competition championship series held in Shanghai. The author was mainly responsible for the mechanical structure and circuit design. The innovation of such a robot was the methodology of abating the robot's moment of inertia with a specific mechanical design which allocates the parts of the robots properly under force analysis simulation. The author further improved the structural design applied to Ares 2.0, an optimized version with energy-absorbing material. The author and his team won the 3rd Place honor of the 2017 FMB championship (Featherweight Category) in Shanghai, the Final Eight of 2018 FMB championship All-Star Invitational (Featherweight Category, International Group), and the 4th Place of FMB championship (Featherweight Category, Domestic Group) respectively.

***Keywords* — Wheeled mobile robot**

A. *The Mechanical Design of "Ares"*

Since the WMR was designed for combat competition, the requirement of the strength of such a robot should be considered firstly and foremost. Its frame was made with alumni materials with three motors inside including two brushless motors in the driving system and one in the weapon system.

The drive system was driven by ESC (electronic speed control) as well as the weapon drive system. The 20:1 planetary reducer was selected to satisfy the speed needs.

Several aspects should be considered while designing the weapon system, including its inertia, strength, the number of teeth attached to it, the teeth number, the weapon and the robots' speed.

A titanium alloy made drum spinner was purposed with the design under the definition of the fitness function, which weights all the demanded characteristics that should be minimized.

$$fit = \frac{w_1}{h^2} + w_2(C_x^2 + C_y^2) + \frac{w_3}{c^2} \tag{1}$$

Fig. 1. Ares

The w_1, w_2, w_3 are specified weights factors that importance of, respectively, the tooth bite (h), the drum balancing (C_x and C_y), and its convexity (c).

The proper design of the drum spinner as the weapon system, escalates the power and enables the robot with a more uncomplicated manipulation in which the influences of the gyroscopic inertia produced could be alleviated.

The newly "Ares 2.0" was designed by the author in 2018 particularly adding the usage of PE board as cushion material to absorb the energy from impacts, as shown in Fig. 2. Besides, the strengthened frame was cast in one body.

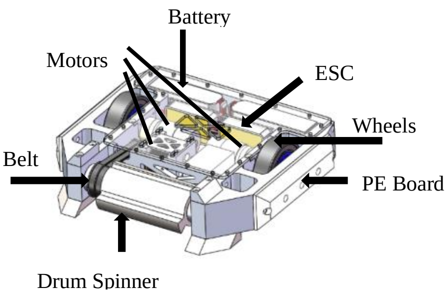


Fig. 2. Ares 2.0

B. *The Manipulation of "Ares"*

All of the three motors are driven by ESC and powered by lithium batteries and controlled manually through the remote controller.

The differential speed mechanism was utilized this two-wheel robot which enables the robot with omnidirectional moving capacity. The maxim speed of the robot was approximately 5 m/s.

$$v = \frac{v_l + v_r}{2}$$
$$w = \frac{v_r - v_l}{l}(rad/s) \quad (2)$$
$$r = \frac{v}{w} = \frac{l(v_r + v_l)}{2(v_r - v_l)}$$

The v_l and v_r represent the left and right wheels' speed which r represents the turning radius use the differential speed mechanism.

II. HUMANOID ROBOT JET-HR1

To replace human beings to carry out dangerous missions, such as search and rescue operations in the earthquake-stricken areas or military actions, the idea of designing a jet-powered humanoid robot was proposed. The innovation was the utilization of a duct-fan propulsion system which improves a humanoid robot's ability to step over a broad ditch with a height difference between the two sides. Jet-HR1 was capable of accomplishing large obstacle-crossing, up to 97% of the robot's leg length, and a height difference of 100mm between two sides. The author mainly participated in the hardware modifications of the robot and certain experiments.

***Keywords* — Humanoid Robot, Ducted-fan system**

A. *Design Concept of Jet-HR1*

The prototype robot, Jet-HR1 (Fig. 4) was composed of 12 servo motors with 12 DoFs and weighs about 6.5 kg. The propulsion system mainly comprised two ducted fans installed in the front end of each foot. The location makes the arm of thrust as long as possible while the swing foot extends. It is helpful for the thrust moment to balance the gravitational moment of the robot. With DC 24 V power, the maximum thrust of each ducted fan can be up to 23 N, while its mass is only 232 g. In addition, the thrust can be adjusted from zero to maximum by the Pulse-Width Modulation signal.

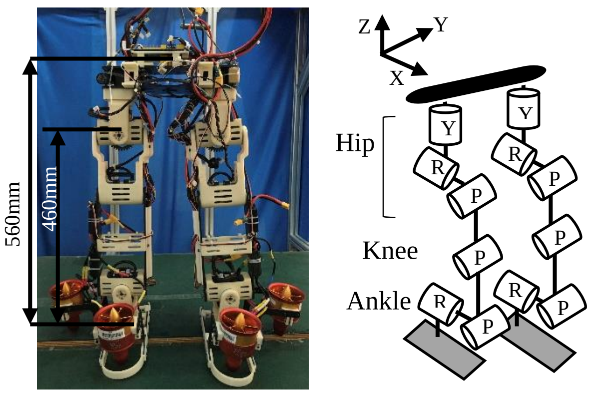


Fig. 3. The Jet-HR1 and configuration of DoF

Fig. 3. indicates the DoF configuration of Jet-HR1 where the hip joints are composed of the hip joint (Yaw), (Roll), (Pitch), consecutively. The detailed specifications of the robot are listed in Table 1. When accomplishing an obstacle-surmounting motion, the quasi-static balance model of the robot is shown in the Fig. 4.

TABLE 1

MAIN SPECIFICATION OF JET-HR1

Component	Description
Weight	6.8 kg
Height	608 mm
Degrees of freedom	12
Length of leg	460 mm
Ducted fan	70 mm, 24 V, 232 g Max thrust 23 N @ 70 A
Joint servo motor	Kodon Kagaku. Co. Ltd. B3M1117, 12 V, 7.8 Nm
Carbon fiber gear ratio	1:2.43
Battery of servo motor	11.2 V, 2600 mAh

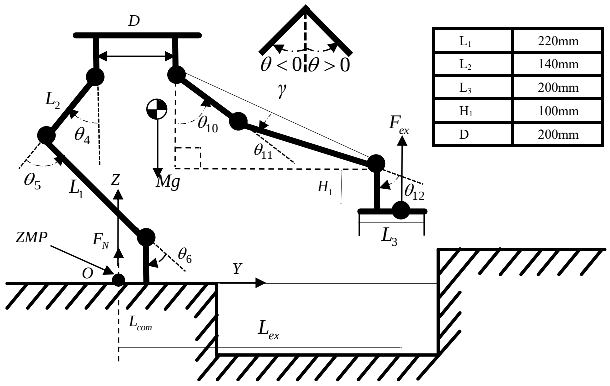


Fig. 4. Quasi-static balance model of Jet-HR1 in 2D[1]

For 2D gaits, the robot's body was symmetrical on both sides of the side plane, which was vertical to the ditch. As a result, the balancing problem of the robot can be simplified to only one plane. Therefore, we used the 2D gaits in the motion of stepping over a broad ditch at the early stage.

Further, for 3D gaits, during quasistatic balance, the robot was assumed to move slowly, and the inertia force resulting from the velocity and acceleration was small and omitted. As a result, during stepping in 3D, only three types of force loading on the robot were counted: gravity, thrust, and the supporting force of the ground. Fig. 5. shows the quasistatic balance model of Jet-HR1 in 3D stepping.

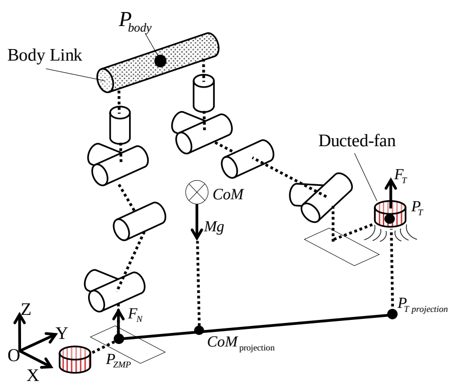


Fig. 5. Quasistatic balance model of Jet-HR1 in 3D

With the proposed method and algorithms, the prototype robot Jet-HR1 could step over a ditch with a span of 450 mm (as much as 97% of the length of the robot's leg) both in 2D and 3D stepping.

Nevertheless, the DoFs configuration of Jet-HR1 has certain limitations. The configuration with the hip joint (Yaw) linked with the waist is incapable of using the whole leg length to span distance when using this 2D gaits strategy.

Here we defined several main limitations of Jet-HR1:

- Low precision: gear backlash.
- Limited dynamic performance: servo motor with low precision and low torque
- Limited workspace: Y-R-P hip joint configuration

Further, since two ducted fans enable the robot with the capacity of stepping over a large ditch, we assumed that more ducted fans installed could provide the robot with more versatile capabilities like jumping, even flying.

Therefore, according to the determined limitations described above and our concepts of employing more numbers of ducted fans, the general design concept of Jet-HR2 was derived.

III. Jet-Powered Humanoid Robot Jet-HR2

Reflected on our previous design of Jet-HR1, we dedicated to design a more versatile machine. The Jet-HR2 (Fig. 6) has 12 DoFs with 6 ducted-fans installed at the pelvis and feet to have the capacity of flight, contact locomotion, and manipulation. As the author's bachelor thesis, the mechanical system of the robot was firstly designed, composed with modular joint featured with light-weight, high-precision, and high torque. Then, based on the performance parameters of the robot's hardware, the author accomplished certain basic motion simulations in PyBullet, a simulation platform based on Python. The result of the simulation as well as the experiments indicated that the prototype robot Jet-HR2 could satisfy our initial requirements.

***Keywords* — Jet-powered humanoid Robot, modular joint**

A. *Design Concept of Jet-HR2*

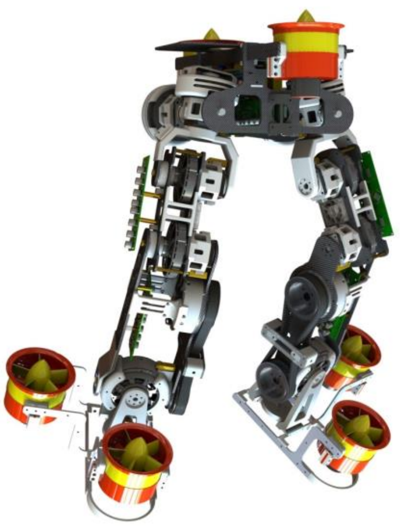
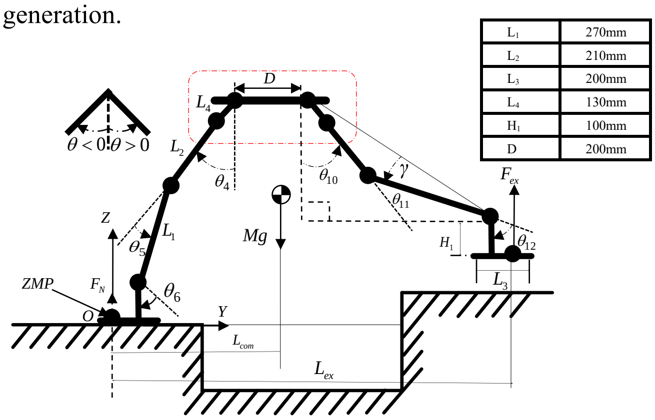


Fig. 6. Jet-HR2

To address the limitations of Jet-HR1 above, we firstly considered to change the DoF configuration. Optimization of the DoF configuration could enhance the two-dimensional (2D) spanning distance with a larger workspace.

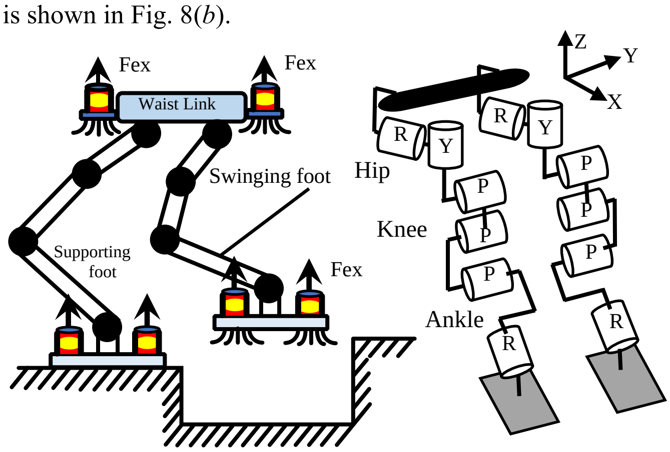
The quasi-static balance model of Jet-HR2 is shown in Fig. 7. The Jet-HR2 can use the whole leg length when stepping over a large ditch (L_{ex} would be maximized as shown in Fig. 7.), compared with the parameters of the first generation.



L_1	270mm
L_2	210mm
L_3	200mm
L_4	130mm
H_1	100mm
D	200mm

Fig.7. Quasi-static balance model of Jet-HR2

The configuration of Jet-HR2 is shown in Fig. 8(*a*). The hip joints are composed of the hip joint (Roll), (Yaw), (Pitch), consecutively. Second, we employed multiple ducted fans (JP90 from Shenzhen JP. Co., Ltd.). Each ducted fan is only 488 g, while its max thrust can achieve 5.1 kg at 44.4V DC power. The configuration of the ducted-fan propulsion system is shown in Fig. 8(*b*).



(*a*) (*b*)

Fig 8. Ducted-fan and DoF configurations

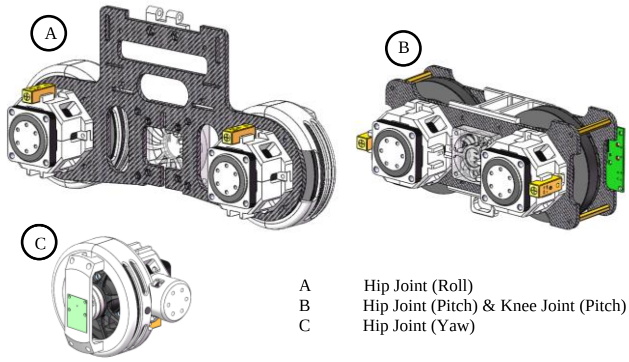
Third, the author designed a light-weight, high precision, and high-torque joint module with the combination of brushless motor (U8 Lite KV150 from T-Motor. Co., Ltd.) and Harmonic driver which improves the control and reduces the error value between the simulations and dynamic motions. Details would be discussed in the next section.

Utilizing the main improvements described above, the overall mechanical property is enhanced as well as being capable of accomplishing more complicated dynamic motions in further researches.

B. *Mechanical Design*

The author started from the design with a single module. Such a module addressed the issues that remained in Jet-HR1 as discussed in the preceding text. Eight joints of the Jet-HR2 are joints based on motor and Harmonic reducer. Such a modular joint is integrated with motor, reducer, and sensor (including magnetic encoder and proximity switch) magnetic encoder is responsible for obtaining parameters from the motors. The proximity switch is designed to correct the zero position (Initial position). The weight of the module is 604g and with very high torque and precision.

The light-weight, high torque, and high precision modular design is utilized in the following parts, as shown in Fig. 9.

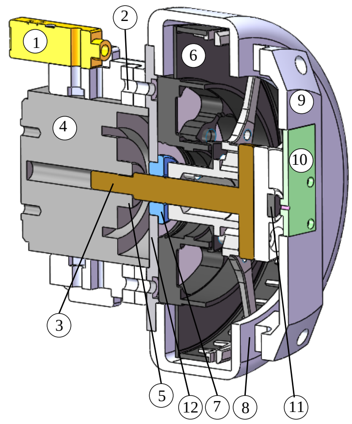


A Hip Joint (Roll)
B Hip Joint (Pitch) & Knee Joint (Pitch)
C Hip Joint (Yaw)

Fig. 9. The modular design of hip joints and knee joint

The figure gives an overview of the drives, starting from the hip joint (Roll) ‘A’. Note that the hip joint (Pitch) and knee joint were set on the same carbon board and they share the same structure.

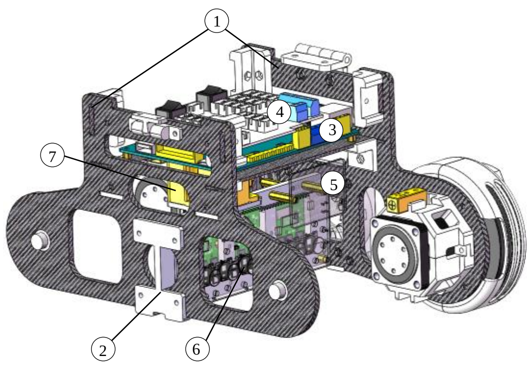
The design and mode of operation of the modular joint are illustrated by Fig. 10. which shows the coordination of motor and reducer.



1 Proximity switch
2 Harmonic Reducer Set
3 Steeped Shaft
4 Harmonic Drive
5 Wave Generator
6 T-Motor U8-Lite KV150
7 Flange Bearing
8 Protective cover
9 Sensor set
10 Hall sensor (Encoder) AS5047P
11 Magnet
12 Carbon pedestal

Fig. 10. Harmonic drive-based revolute joint, here: hip joint (Yaw) type ‘C’

Fig. 11. shows the pelvis structure.

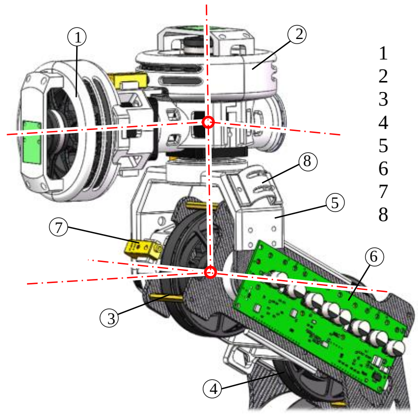


1 Pelvis Carbon Frame
2 Pelvis Alumni Link
3 STM32 F4
4 Extended Circuit Board (1)
5 Extended Circuit Board (2)
6 Motor Driver
7 IMU

Fig. 11. Pelvis base body

The pelvis part holds two hip joints (Roll) with the mounting of the ducted-fan system containing other parts like motor drivers and battery.

Fig. 12. shows the mechanical design of the hip and knee joints. The impact design could help to alleviate the inertia effect.



1 Hip Joint (Roll)
2 Hip Joint (Yaw)
3 Hip Joint (Pitch)
4 Knee Joint (Pitch)
5 Rotation Segment
6 ODrive
7 Proximately switch
8 Wire slot

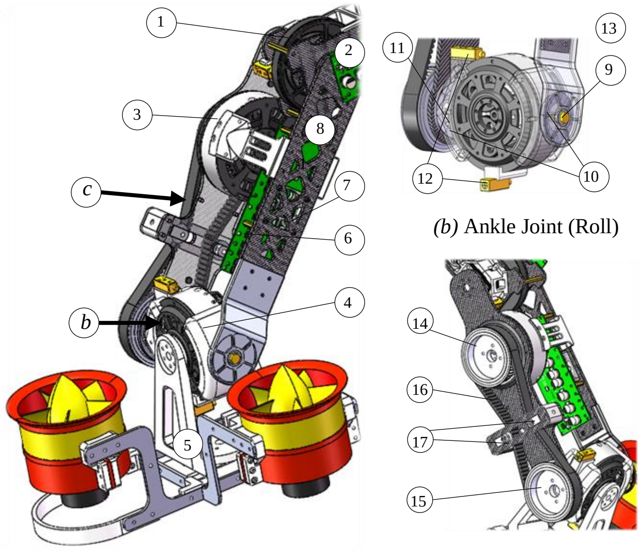
Fig. 12. Hip joints and knee joint

The three-DoF hip joints are allocated separately, with one hip joint (Roll) on the waist. The hip joint (Yaw) is located the gap between the two frames of the pelvis. The hip joint (Pitch) and the knee joint (Pitch) are deliberately aggregated.

The ankle joint design was different from the other eight joints mentions above. The dissimilarity is the integrated actuator used here.

As shown in Fig. 13. The two-DoF ankle joints are based on actuator A-80-9 with a 9:1 reduction rate.

The reason to raise the ankle joint (Pitch) toward a high position on the shank is the inertia consideration. Such a design is advantageous to control. The two motors are, linked with the synchronous belt, shown as Fig. 13 (*c*). Two idlers are fixed to adjust the tension.



(b) Ankle Joint (Roll)

(a) Overview

(c) Synchronous belt drive

1 Knee Joint
2 Thigh segment
3 Ankle Joint (Pitch)
4 Ankle Joint (Roll)
5 Foot Segment
6 Motor driver: Odrive
7 Shank segment
8 Bilateral Support design
9 Thrust needle roller bearing
10 Thin-wall bearing
11 Proximity switch
12 Ankle link
13 Pulley (driving)
14 Pulley (driven)
15 Synchronous belt
16 Idler (adjustable)

Fig. 13. Mechanical design of the Shank

C. *Specifications*

The height of the robot is 700 mm, and the total weight is about 15kg (battery included). Details specifications of Jet-HR2 is listed in the Table 2.

The robot's dimension is shown in Fig. 14. And the assembling of the robot is still under progress, as shown in the Fig. 15.

TABLE 2

MAIN SPECIFICATION OF JET-HR2

Component	Description
Weight	15 kg
Height	700 mm
Degrees of freedom	12
Length of leg	480 mm
Ducted fan	90 mm, 48 V, 488 g
	Max thrust 50 N @ 90 A
Joint motor	T-Motor Co. Ltd.
	U8-Lite KV150/A-80-9
Reducer	Harmonic CSF-11-50-1U-CC-SP
	Reduction ratio: 50:1
Battery of servo motor	44 V, 5200 mAh

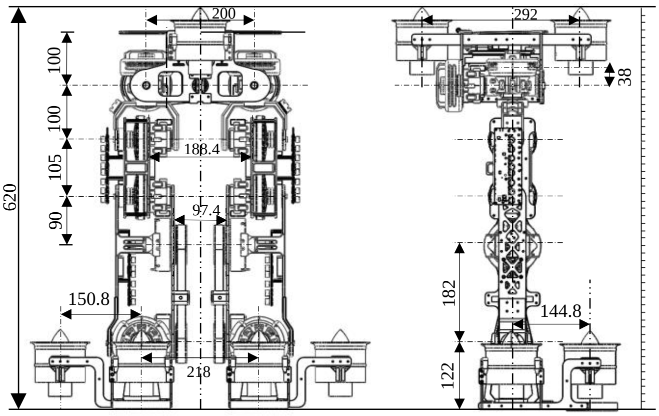


Fig. 14. The Jet-HR2's dimensions

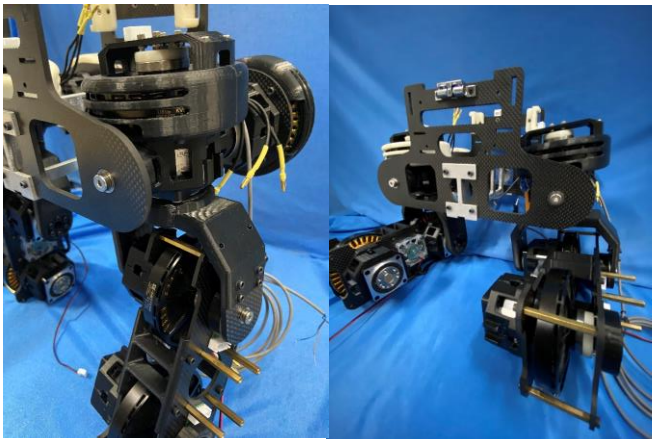
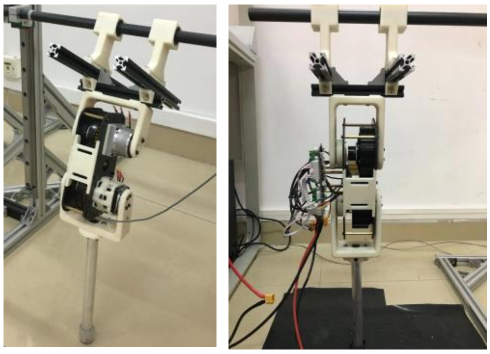


Fig. 15. Eight joints (Undergoing)

D. *Experiment*

To evaluate the performance of the module design and the actuator, the author designed two test legs, shown in Fig. 16. The first test leg (*a*) was composed which two motors and Harmonic drivers. The second leg (*b*) is composed of two actuators.



(*a*) (*b*)

Fig. 16. Test Legs

This jumping experiment was carried out to examine the jump capacity based on the ankle joint's motor to evaluate the performance. The conditions are shown in Fig. 17.

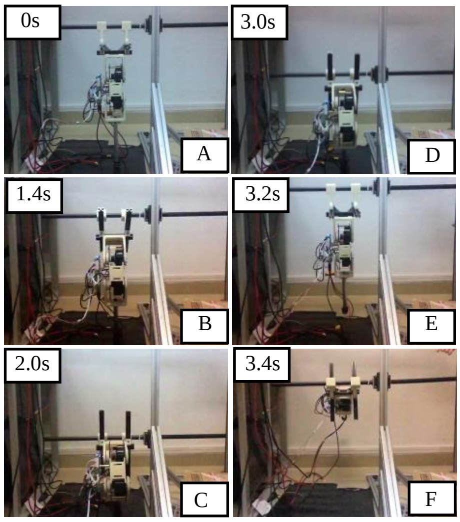


Fig. 17. The jump test based on motor: A-80-9

The experiment was performed two times in total; the approximately jump height could reach 100mm. The above Image sequences illustrate one of the tests. As we can see, both of the rotation angles are more than 90 degrees, in frame C. In frames D to F, the acceleration of motors exert power on the shank in 0.4s to take off.

The load capacity experiment was carried out to evaluate the structural strength of the hip and knee joints module shown in Fig. 18. A single thigh was set and 20 kg weight was suspended on it.

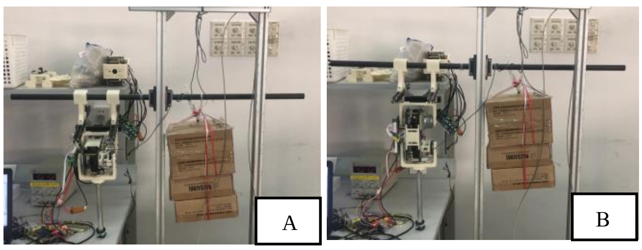


Fig. 18. The Load capacity test based on Hip and Knee Joint (B)

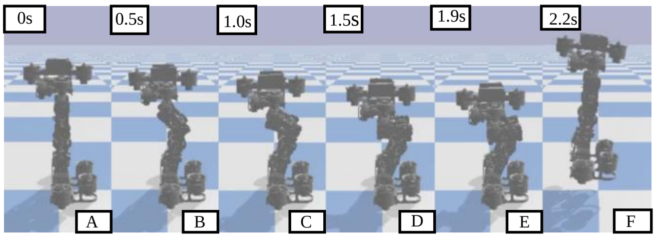
Simply put, the result of the experiment indicates that such modular joint design is capable of accomplishing various complex dynamic motions.

E. Simulations

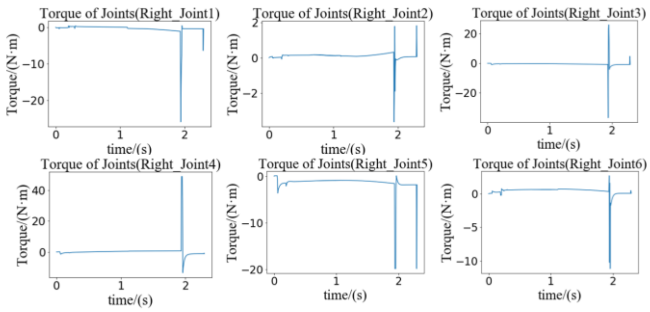
In order to verify the parameters of joint performance and ducted propulsion system, we import the model of Jet-HR2 into the PyBullet simulation platform to verify relevant indicators, including:

- Take off simulation: can Jet-HR2 complete take-off action under the vertical thrust of full power ducted propulsion system
- Jump simulation: evaluate whether the jump action can be completed within the allowable range of joint torque and rotation speed of the robot when the ducted fans are on/off.

Fig. 19 shows the vertical jumping simulation in which the ducted-fan propulsion system was not activated.

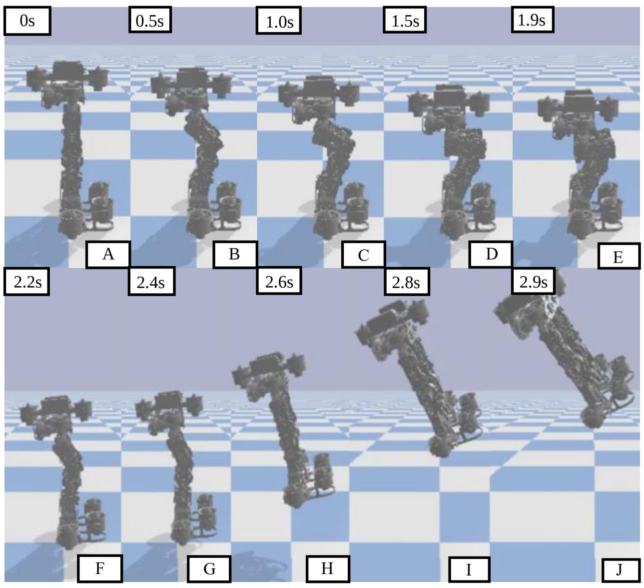


(a)

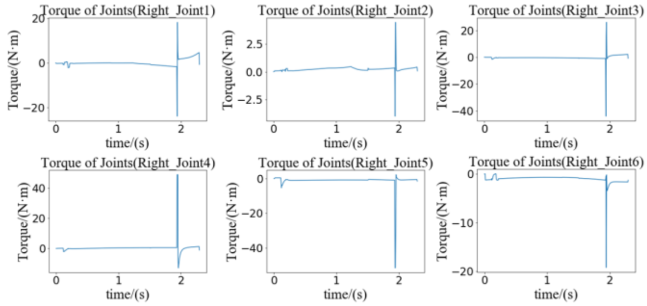


(b)

Fig. 19. Jump simulation (without ducted-fan)



(a)



(b)

Fig. 20. Jump simulation (with ducted-fan)

Fig. 20. shows the vertical jumping simulation employed the four ducted-fan propulsion system on the feet (with full thrust). Besides, two simulations were assumed with the same parameters, including the starting position.

The simulation result can be concluded that when the parameters of the robot are fixed, the jumping performance of the robot can be greatly improved by employing the ducted-fan propulsion system.

To evaluate the dynamic stability of the robot in flight, the hovering simulation action based on four ducted-fan was conducted. Here we set the feet to be exactly symmetric and regarded such a position to be alike four-rotor aircraft, as shown in Fig. 21.

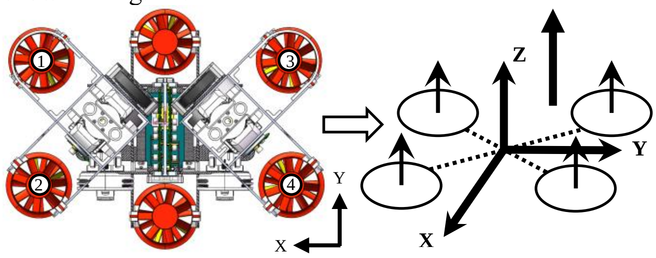


Fig. 21. Target attitude of hovering

The PD controller can effectively adjust the angle of roll and pitch directions, and correct the angle of hovering attitude by adjusting the thrust of the ducted-fan. As shown in Fig. 22.

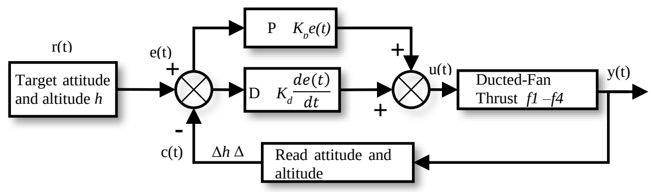
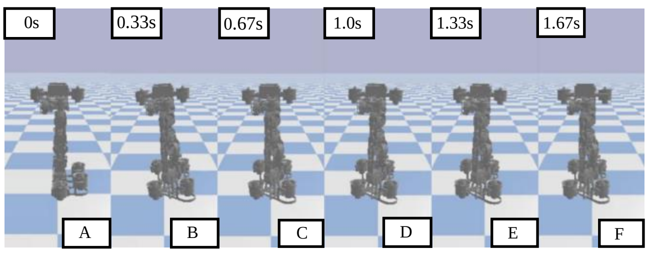


Fig. 22. PD control strategy

The simulation result is shown in Fig. 23. The maximum deflection angle of pitch is about 0.0002 rad, and that of roll is about 0.075 rad. After the robot changes to the hovering posture of the target, both pitch and roll tend to zero.



(a)

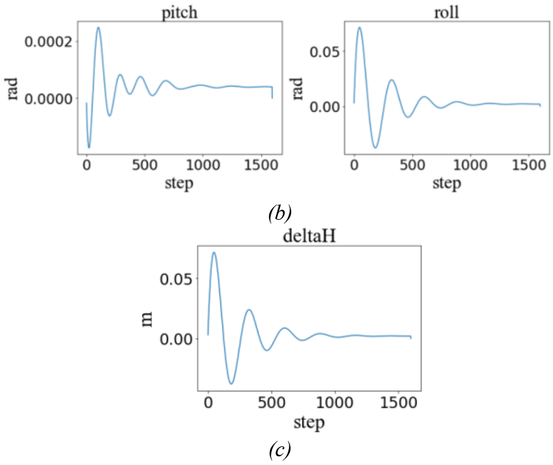


Fig. 23. Hovering simulation

F. Embedded Control System Design

Beyond the mechanical system, the embedded control system was designed as well, as shown in Fig. 24.

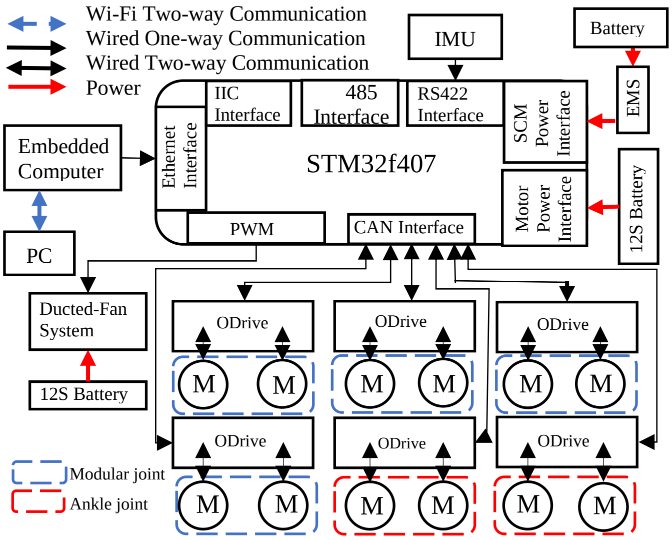


Fig. 24. The Embedded Control System

Several different real-time communication systems were evaluated, including CAN, PWM, and other proprietary implementations of real-time Ethernet. And this turns out to be the optimum solution.

The author mainly participated in the control of twelve motors through motor driver: ODrive. Each motor (without the ankle) has an AS5047P encoder which sends position information towards ODrive. The main advantages of using CAN-based communication are that the CAN could be set up easily and many devices already contain standard CAN configuration, the host PC for example.

G. Discussion

The aforementioned experiments show the potential for robots to accomplish with versatile motions. Yet, the project is still under progress, and improvements are needed. Our recent work focused on long jump motion with the utilization of four ducted fans (2 on the waist, the other 2 installed on the robot's feet).

Acknowledgments

I would like to acknowledge Prof. Zhifeng Huang, and the members of our laboratory for dedicating their works on these interesting projects.

References

[1] Huang, Z., Liu, B., Wei, J., Lin, Q., Ota, J., & Zhang, Y. (2017, November). Jet-HR1: Two-dimensional bipedal robot step over large obstacle based on a ducted-fan propulsion system. In *2017 IEEE-RAS 17th International Conference on Humanoid Robotics (Humanoids)* (pp. 406-411). IEEE.