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EARLY DEVELOPMENTS OF A PARALLELLY ACTUATED HUMANOID, SAFFIR

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ABSTRACT

This paper presents the design of our new 33 degree of freedom full size humanoid robot, SAFFiR (Shipboard Autonomous Fire Fighting Robot). The goal of this research project is to realize a high performance mixed force and position controlled robot with parallel actuation. The robot has two 6 DOF legs and arms, a waist, neck, and 3 DOF hands/fingers. The design is characterized by a central lightweight skeleton actuated with modular ballscrew driven force controllable linear actuators arranged in a parallel fashion around the joints. Sensory feedback on board the robot includes an inertial measurement unit, force and position output of each actuator, as well as 6 axis force/torque measurements from the feet. The lower body of the robot has been fabricated and a rudimentary walking algorithm implemented while the upper body fabrication is completed. Preliminary walking experiments show that parallel actuation successfully minimizes the loads through individual actuators.

1. INTRODUCTION

Emergency first responders are the great heroes of our day, having to routinely risk their lives for the safety of others. Developing robotic technologies to aid in such emergencies could greatly reduce the risk these individuals must take, even going so far as to eliminate the need to risk one life for another. In this role, humanoid robots are a strong candidate, being able to take advantage of both the human engineered environment in which it will likely operate, but also to make use of the human engineered tools and equipment as it deals with a disaster relief effort. In that vein, SAFFiR (Shipboard Autonomous Fire Fighting Robot) is being developed to further the technologies necessary to achieve that ultimate goal.

There are of course many existing humanoid robotic designs such as, KAIST University's HUBO[1-3], Honda's ASIMO[4], Waseda University's Wabian-2 [5,6], and Technical University of Munich's Johnnie and LOLA[7-10], and all have significant achievements to their names. They also share many similarities in both their architecture and control strategies. Specifically, nearly all of the aforementioned designs rely on harmonic drives for speed reduction between the motor and the joint, which tend to force researchers to design humanoid limbs as serial manipulators. This mechanical architecture has been developed in conjunction with stiff position controlled joint trajectories and motions, for which the harmonic drive is less than ideal due to its compliant nature [3,11].

SAFFiR was designed to break out of this mold and investigate and take advantage of both compliant control schemes [12,13] and a parallel architecture employing linear actuators. It is hoped that this new compliant parallel architecture will enable more robust performance in difficult environments in which SAFFiR and future emergency response robots are expected to operate. This paper will discuss the design of the SAFFiR, with emphasis on the lower body, as well as experimental results from walking tests which validate the parallel actuator arrangement.

2. SYSTEM OVERVIEW

SAFFiR, as seen in Figure 1, is a humanoid robot that will stand 1.6[m] tall when completed. It features 33 DOF, which includes two 6 DOF legs and arms, a 1 DOF waist, 2 DOF neck, and 3 DOF hands, oriented as shown in Figure 2. The general proportions of the robot can be seen in Table 1 and the range of motion, power, and approximate reduction ratio of each DOF can be seen in Table 2. SAFFiR employs parallelly actuated joints in the lower body; therefore, the available power in each direction is the maximum available assuming the leg is loaded in only that direction. When completed, it is expected that the robot will weigh 40[kg].

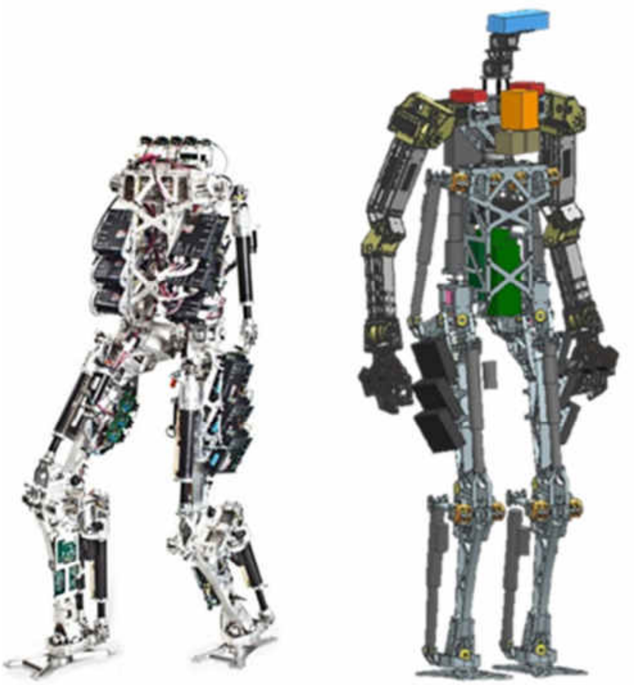

Figure 1: Currently state of completion of SAFFiR on left and proposed final CAD model.

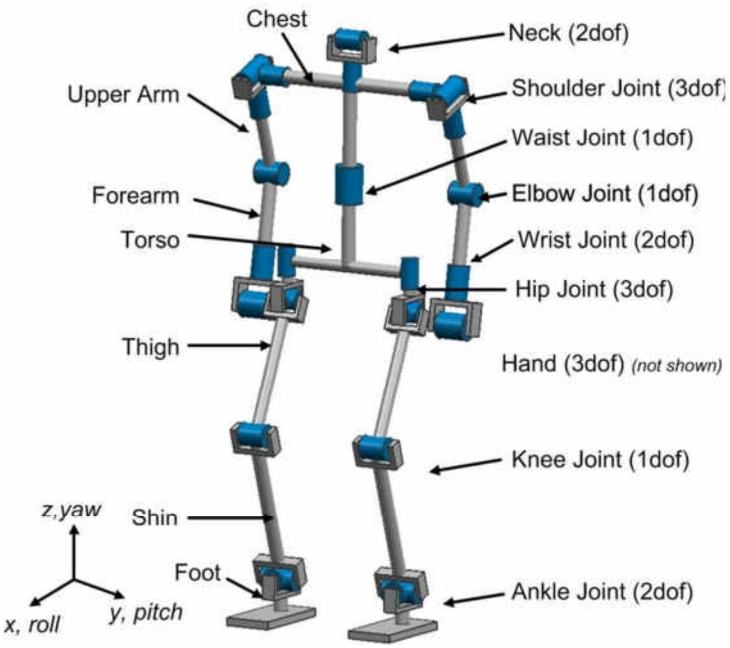

Figure 2: Kinematic arrangement of SAFFiR.

Table 1: Specifications of SAFFiR.

General	Height	160 cm
	Weight	40 kg
	Total DOF	33
Legs	Thigh length	380 mm
	Shin length	380 mm
	Foot height	40 mm
	Hip width	195 mm
Arms	Shoulder width	460 mm
	Upper arm	250 mm
	Lower arm	200 mm

Table 2: Range of motion, mechanical advantage (between motor and limb), and power of SAFFiR's leg joints.

	ROM [deg]	**Peak power**	**Peak gear reduction**
Hip Yaw	-25, 10	100 W	230:1 Planetary
Hip Roll	-23, 23	400 W	320:1 Ballscrew
Hip Pitch	-45, 45	400 W	350:1 Ballscrew
Knee Pitch	0, 90	200 W	370:1 Ballscrew
Ankle Pitch	-40, 50	200 W	350:2 Ballscrew
Ankle Roll	-20, 20	200 W	180:1 Ballscrew

Six DOFs are used in the legs to make the feet fully independent of the torso, allowing for complete control of the torso while in single support. The same is true of the arms, which provide 6DOFs to the hands. Three DOF hands are notionally used, having three one DOF fingers.

The robot is primarily fabricated from 6061 Aluminum because of the materials high strength to weight ratio and ease of machining as compared to other Aluminum alloys. Each skeletal joint of the lower body is supported by two preloaded angular contact bearings to ensure there is no play in the structure. The joints of the upper body rides on preloaded cross roller bearings in each DOF.

3. DESIGN OVERVIEW

Current humanoid designs are almost all serially actuated. This trend is in part due to the limits of high gear reduction revolute actuators based on the harmonic drive. It is worth investigating other architectures as the current trend has several drawbacks. In a serial configuration, actuators cannot share an applied load and must therefore be larger and more powerful. Position errors are summed across the joints which decreases accuracy. A serial architecture also has higher inertias and therefore lower accelerations. Harmonic drives also have a high stiffness and very little dampening which can create troublesome resonances in the robot [3,11] in addition to being counterproductive to the stiff position controlled motions generally employed.

The SAFFiR architecture employs both a unique actuator and actuator arrangement to achieve new gains in mobility and agility as compared to conventional humanoid robots. First, a parallel actuation architecture (in which one joint comprised of several DOFs is spanned by an equal number of actuators) is used to enable higher torques and power in certain motions, improve positional accuracy, and reduce backlash. The parallel architecture also has the added benefit of centralizing and simplifying the robot structure (which reduces weight) as well as consolidating more of the actuator mass nearer to the center of mass. The arrangement of actuators can be seen in Figure 3.

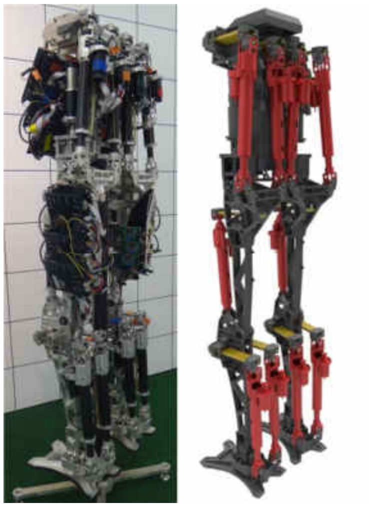

Figure 3: Linear actuators shown in red against SAFFiR's structure. Compliant beams shown in yellow.

This architecture drives the selection of actuators. Linear actuators are employed to make use of highly efficient, stiff, and low backlash ballscrews as the gear reduction mechanism and facilitate the addition of an elastic member in series. Titanium cantilevered beams, as seen in Figure 4, serve as the elastic members and can be individually stiffened or even locked out. This configurable compliance in conjunction with a very stiff and efficient actuator enable both position and force controllable modes to operate on the robot. Having both modes on SAFFiR gives us ability to experiment with the compliance and its appropriateness at each joint, a topic for future research.

Simple levers are used to transmit linear motion to a rotation about a joint. This configuration is limited by the fact that for any linear actuator and lever, the largest range of motion between singular positions (in which the mechanical advantage goes to zero) is 180 degrees. Therefore, in the case of SAFFiR, all the joints were designed to have maximum mechanical advantage at the middle of their ranges of motion so as to maximize the MA over the remaining range. Four bar mechanisms in which the driven and driving link are connected to ground were investigated, but any improvement was on the order of 10% and not worth the additional complexity. Other types of linkages, e.g. the Hoeken's linkage, are under investigation for future revisions.

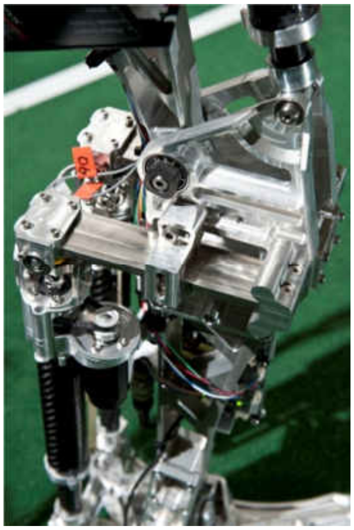

Figure 4: Titanium compliant members in series with the two ankle actuators.

4. DESIGN DETAILS

4.1. Actuators

Custom linear serial elastic actuators capable of force control were designed for SAFFiR to save both weight and volume [14,15]. Lee presents a detailed analysis of the design in [16], but an overview is provided here. Each actuator is powered by either a 100 or 200 Watt Maxon EC 4-pole brushless DC motor running at 48 volts. The motor in turn drives a precision rolled ballscrew through a one-stage belt reduction. Power is delivered to the joint through the moving ballnut and attached carbon fiber tube. The ends of the actuator are affixed to the robot through u-joints, which both fully constrain the actuator as well as limit the ballnut rotation relative to the ballscrew.

Accurate and high bandwidth force control is achieved using feedback from Futek™ LCM-200 inline load cells in each actuator and Futek signal conditioning boards. Compliant titanitum beams serve both as the series elastic member, and the mounting point for the actuator on the robot [17]. The beams are relatively stiff at 150-500[kN/m]. Closed loop control of the actuator force is handled by custom motor controller code implemented on Maxon EPOS2 Controllers. In cases for which compliance is not needed, the beams can be fixed and high gain position controllers run for accurate trajectory control. The linear actuator can be seen in Figure 5.

The yaw DOF in the hip is the only DOF in the lower body that is not actuated with a linear actuator nor has any compliance. Instead this DOF is controlled in position mode through a planetary gear reduction unit.

The upper body is driven by a new line of actuators from the ROBOTIS Corporation™ called the Dynamixel-Pro™. They are a complete servo-motor package, including motor, controller, and gear reduction. Furthermore the housing is structural, and the output supported by a robust cross roller bearing such that when implemented the motors form an integral part of the upper arm structure. They controllers support CAN and RS-485 communication protocols. A summary of the actuator characteristics can be seen in Table 3.

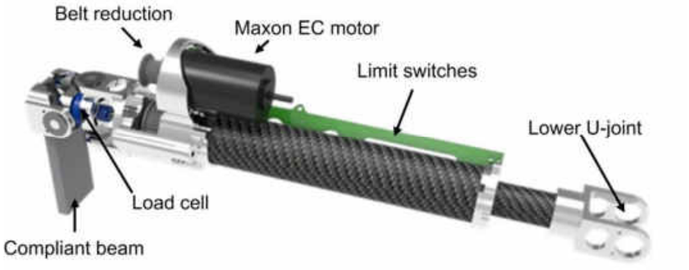

Figure 5: Rendering of custom electric linear series elastic actuator with Titanium compliant beam.

Table 3: Actuator specifications as used on SAFFiR.

Type	**100W Linear**	**200W Linear**	**20W Rotary**	**100W Rotary**	**200W Rotary**
Weight [g]	653	735	320	642	760
Force	300[N]	500[N]	5.5[Nm]	21[Nm]	32[Nm]
Max Force	1000[N]	1600[N]	11[Nm]	39[Nm]	48[Nm]
Max Speed	0.2 [m/s]		28[rpm]	35[rpm]	35[rpm]
Joint Used	Hip/Ankle	Knee	Wrist	Elbow	Shoulder

4.2. Hip

As alluded to earlier, the hip joint employs a hybrid parallel/series arrangement. The yaw DOF is driven directly by one actuator, while the pitch and roll DOFs are parallelly driven by two linear actuators. The hip pitch and roll typically require more power, torque, and precision than the yaw, and so were chosen to be driven together to maximize the benefit of parallel actuation during a walking cycle. The highest power draw occurs about pitch during the accelerations of the leg swing, while maximum torque is needed for the stance roll joint to support the remainder of the robot. Because of the length of the leg, the precision of the roll and pitch have a greater effect on foot placement than yaw. The two associated actuators start at the top of the torso and terminate at the top of the thigh. They are nominally placed on the torso to minimize the leg inertia. The assembled torso and hip joints can be seen in Figure 6.

The two linear actuators of the hip drive the pitch and roll DOFs through two effective levers (defined as the perpendicular length between the actuator and the axis of rotation). The roll levers are maximized to provide a large degree of torque about this axis while keeping interferences from occurring. With a hip width of 190[mm], the roll lever was made 65[mm] long for a gear reduction of 320:1. The lever arm for pitch was made slightly longer as there were fewer packaging constraints. It is 70[mm] long for an overall reduction of 350:1.

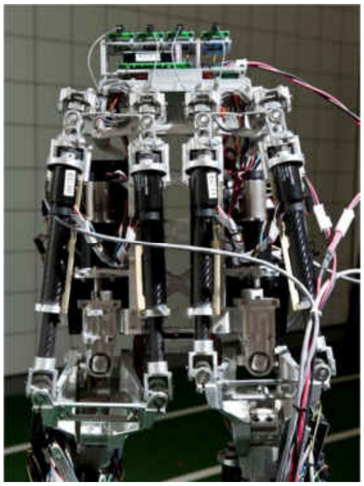

Figure 6: Parallel hip actuators as seen on the robot.

4.3. Knee and Ankle

The knee and ankle are more straightforward than the hip. The knee is driven by a 200W linear actuator to handle the higher power and force output required by certain motions such as bent knee walking or squatting. As is, this motor operates at roughly 40% of its continuous capability, indicating the motor is properly sized considering more weight will be added to the robot as it develops.

The lever arm for the knee is 75[mm] long and is biased so that when the knee is bent, the mechanical advantage increases, and when straight, the advantage decreases. This allows for greater knee speed when walking, and more torque when bent for squatting. The knee can be seen in Figure 7.

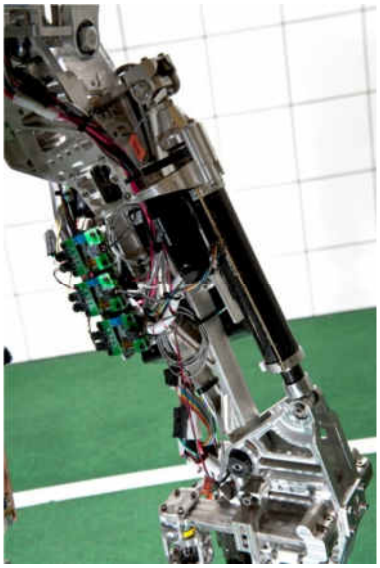

Figure 7: Details of knee actuator.

The ankle has two DOFs, pitch and roll, arranged in that order and also controlled in a parallel manner. The ankle joint is unique in that the dynamic requirements of the joint are less severe, i.e. the foot is lightweight and requires little torque to move when in the air, and when on the ground, can only exert as much torque on the ground as the support polygon and robot weight will allow. Therefore, the lever arms can be smaller; for roll they are 37[mm], and pitch they are 70[mm].

Figure 8: Parallel ankle actuation.

4.4. Upper body

The upper body consists of two six DOF arms, with a three DOF shoulder, one DOF elbow, and two DOF wrist. The current hands have three fingers, each with one DOF capable of grasping a variety of objects. The upper body is actuated solely with serially arrange revolute actuators in order to achieve the large range of motion necessary. This also ensures uniformity of communication protocols across the entire upper body. The orientation of each actuator can be seen in Figure 2. The first two actuators in the arm are of the 200[W] variety, the second two 100[W], and the final two 20[W].

The hand consists of three independent 1-DOF fingers. Each finger is made up of two links, where the second link position is dependent upon the first. The fingers are driven by ROBOTIS EX-106™ motors.

Finally, the neck includes two DOFs, a yaw followed by a pitch to allow the sensors onboard the head a wide field of view. Both utilize the 20W Dynamixel™ Pro motor.

5. SENSORS AND COMPUTATION

SAFFiR utilizes a distributed control system. High level motion control is done on a dual core 1.6[GHz] FitPC3™ that also handles the kinematic calculations and communication using the lightweight Linux distribution, Arch™. Low level motor control, that which handles motor current, motor position, and actuator force, is done on the Maxon EPOS2™ motor controllers located on the front of the torso and side of the thighs. Communication between the PC and the controllers is achieved through a CAN network running the CANOpen protocol. Two CAN network cards, PEAK™ PCI-Express units, are used for a total of 4 channels. One channel is utilized per leg, one for the force torque sensors (as they run at a lower baud rate), and one channel remains for the upper body. The CAN network is the slow link in the control loop chain; however, cycle times are only 2[ms].

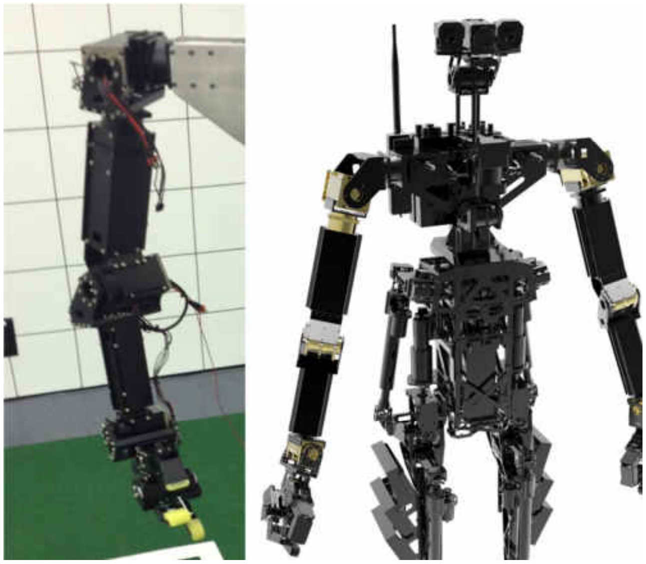

Figure 9: Physical arm on left and render of completed upper body on right.

SAFFiR includes an advanced instrumentation suite for both proprioceptive and exteroceptive sensing. The angular rates, positions, and linear accelerations are attained from a Microstrain™ 3DM-GX3-25 AHRS unit. The robots interactions with the ground are monitored via an ATI Mini-45™ 6-axis force torque sensor in each foot. As mentioned earlier, actuator positions and forces are sensed through the motor controllers, and processed into joint position and torques onboard the FITPC3™. Exteroceptive sensors include stereo FLIR™ cameras for navigation, UV sensors for fire detection, a webcam, and a RADAR proximity sensor for range estimation in smoke filled environments. A Hokuyo LASER range finder is located on the chest for navigation in clear air.

SAFFiR is designed to be operated without a tether, therefore all power is onboard. The power system is separated into two isolated subsystems. The first supplies the motors with power, and consists of two Lithium polymer batteries that provide 10 amp-hours of energy at 48 Volts. It is expected that during normal operation this will provide 30 minutes of power. The second power subsystem runs at 24 Volts and supplies all the computation and sensory devices. All batteries are contained within the torso. Separating the actuator and sensory power systems reduces noise and power interruptions that may occur during demanding motions.

6. RESULTS

The lower body of the robot has been fabricated as seen in the figures above along with portions of the upper body. A preliminary walking algorithm has been implemented on the robot, The algorithm uses simple time based trajectories generated online in conjunction with ankle and hip feedback strategy based on the gyro rates to improve stability. While the algorithm is not particularly noteworthy (and so not detailed here), some of the results are. The forces generated in each actuator from one leg were measured during two strides and are presented in Figure 10. In this figure, dual support and single support phases are denoted by DS, and SS respectively. The blue line represents the inner actuator, and the red line the outer actuator. Positive values signify the actuator is in tension.

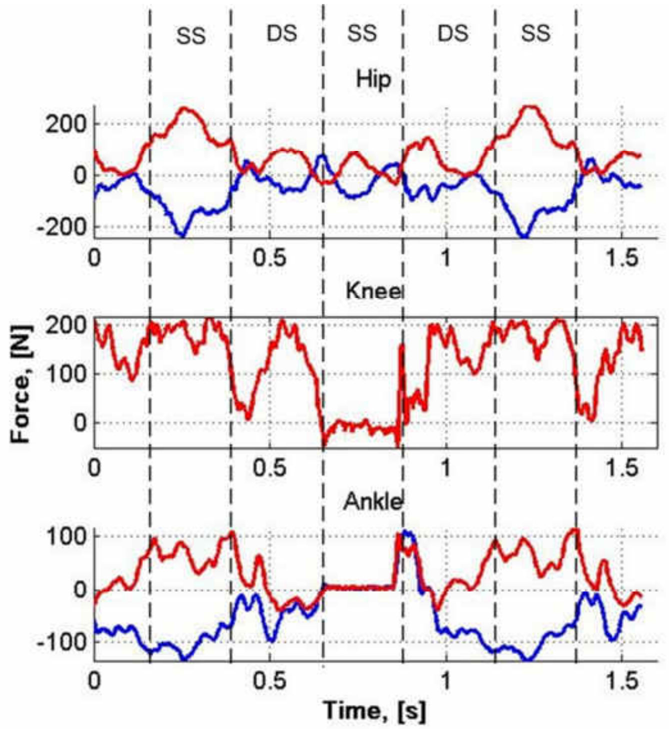

Figure 10: Actuator forces as a function of time for the right hip, knee, and ankle during a walking stride.

The data in Figure 10 is that of the right leg. Around 0.2[s], the left leg lifts from the ground and the robot goes into single support phase with the right leg acting as the stance leg. The left heel strikes the ground at 0.4[s] and momentarily unloads the right knee; the double support phase follows. Both the knee and ankle plots go to zero during the next single support phase when the right leg is in the air. The right heel strike is clearly visible at 0.9[s] in both the ankle and knee.

Most notable from this plot is the distribution of force between the two hip actuators during the first single support phase in which the right leg is the stance leg. Firstly, it is during this phase that the maximum loading of the hip actuators occurs. Secondly, the actuators are nominally acting in equal and opposite directions, meaning the hip is predominantly loaded about the roll axis. The magnitude of the roll torque matched the expected value given the robots weight, hip width, and acceleration. Therefore the parallel actuator configuration chosen complements the loading conditions present. The effort of each actuator to meet the loading requirements of the hip is minimized, which prolongs battery life and increases the load carrying capability of the robot.

7. FUTURE WORK

Preliminary testing has produced positive results thus far, and further development of SAFFiR will continue, most notably, the integration of the complete upper body with the lower. In terms of control, the implementation of walking algorithms that make full use of the force controllable actuators will be the focus of future research.

Several areas of improvement have been identified. The most significant of those are the range of motion limitations inherent in any parallel manipulator configuration. In the case of SAFFiR, the combination of linear actuators and levers as a means to drive the joints restricts the range of motion to approximately 90 degrees before a significant amount (30%) of mechanical advantage is lost.

Therefore careful considerations must be given to the design of the joint and associated actuator placement. As mentioned earlier, it may be beneficially to group some DOFs together as parallel manipulators and others not. For example, the hip and knee pitch DOFs require ranges on the order of 150 degrees for many common motions. It is likely that on future iterations of SAFFiR, these will be actuated independently of other DOFs so as to maximize their range of motion while the remaining DOFs are parallel.

8. CONCLUSIONS

In this paper, the design of a new 33 degree of freedom full size humanoid robot, SAFFiR (Shipboard Autonomous Fire Fighting Robot) is presented. Unlike existing humanoids, SAFFiR employs a parallelly actuated architecture to best utilize the multiple actuators of any one joint. Furthermore, configurable compliance is incorporated into the lower body actuators to enable force controlled walking strategies. A distributed control system allows high bandwidth motor control loops to run independent of the motion control algorithm. Sensory feedback on board the robot includes an inertial measurement unit, force and position output of each actuator, as well as 6 axis force/torque measurements from the feet. Experimental results from walking tests show that during a stride, actuator effort is minimized in the hip due to the parallel architecture.

ACKNOWLEDGMENTS

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