

Upper Body Design of a Humanoid Robot for the DARPA Robotics Challenge

John Seminatore

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Al Wicks, Chair
Alan Asbeck
Steve Southward
Pinhas Ben-Tzvi

22 August 2016
Blacksburg, Virginia

Keywords: Design, DARPA Robotics Challenge, Humanoid
Copyright 2016, John Seminatore

Upper Body Design of a Humanoid Robot for the DARPA Robotics Challenge

John Seminatore

Academic Abstract

Humanoid robots have captured the imagination of authors and researchers for years. Development of the bipedal walking necessary for humanoid robots began in earnest in the late 60's with research in Europe and Japan. The the unique challenges of a bipedal locomotion led to initial robots keeping power, computation, and perception systems off-board while developing the actuators and algorithms to enable locomotion. As technology has improved humanoid and exoskeleton systems have finally incorporated all the various subsystems to build a full independent system. Many of the groups building these platforms have developed them based on knowledge acquired through decades of prior development. For groups developing new humanoid systems little guidance on the pitfalls and challenges of humanoid design exist.

Virginia Tech's robot ESCHER, developed for the DARPA Robotics Challenge (DRC), is the 4th generation full sized humanoid developed at the University. This paper attempts to quantify the design trades and techniques used to predict performance of ESCHER and how these trades specifically affected the design of the upper body. The development of ESCHER became necessary when it became obvious that the original design assumptions behind the previous robot THOR left it incapable of completing the DRC course and the necessary upgrades would require an almost complete redesign. Using the methods described in this paper ESCHER was designed manufactured and began initial testing within 10 months. One and a half months later ESCHER became the first humanoid to walk the 60 m course at the DRC.

The methods described in this paper provide guidance on the decision making process behind the various subsystems on ESCHER. In addition the methodology of developing a dynamic simulation to predict performance before development of the platform helped provide design requirements that ensured the performance of the system. By setting design requirements. ESCHER met or exceeded the goals of the team and remains a valuable development platform that can provide utility well beyond the DRC.

Upper Body Design of a Humanoid Robot for the DARPA Robotics Challenge

John Seminatore

Public Abstract

Long a product of science fiction, humanoid robots have been in development by researchers since the late 60's but still haven't reached their promised potential. The DARPA Robotics Challenge (DRC) was an inducement prize contest held in 2013 and 2015 to help accelerate the use of robotic systems for disaster response scenarios. Team VALOR Virginia Tech's entry into the competition was required to build a completely new humanoid in 10 months, resulting in the Electric Series Compliant Humanoid for Emergency Response or ESCHER. The rapid development of ESCHER was made possible by system engineering and a analysis to ensure ESCHER could meet all the competition goals. At The DRC ESCHER became the first humanoid to walk the 60m course.

Humanoid research labs have used intuition and knowledge gained through decades of experience to design their systems. This paper discusses techniques used to design the upper body of ESCHER as well as modeling and simulation to predict performance when designing a humanoid. By using trade analysis and modeling researcher's new to the field can design to a predicted performance point with confidence in a chiving accurate results.

Acknowledgments

A project the size and scope of ESCHER can not possibly be accomplished by one person, and I would not be here (finally) without the support of a wide variety of people both academically and personally. When the first Grand challenge was announced I could only dream of being involved in something so world changing. To get the opportunity to compete with the best roboticists in the world and earn their respect was an amazing feeling. Thank you to everyone who made this possible.

First I need to thank my family who supported this crazy Idea of mine to give up a promising career to go back to school and completely shift gears. I know they were worried, but I hope I've made them proud and calmed some of their concerns. Second I would like to thank my advisors. Dr. Wicks stepped up to get me through the last part of my thesis and encouraged me to foray into the world of teaching. That opportunity is something I will never forget and something I aim to continue no matter where my career takes me. Dr. Asbeck you helped remind me how amazing what we were doing really was, it's easy to take for granted something you see every day. Your enthusiasm and support won't be forgotten. Dr. Ben-Tzvi in my experiences most professors aren't looking to add to their student load, for you to specifically ask to be added to my committee and take the time out of your busy schedule means a lot. Dr. Southward you were hands down the best instructor I had during my time at VT. Without you I would not be able to say with confidence I am a controls specialist. That you would take time out of your vacation for me is more than I could have asked for.

Of course the members of TREC, previously known as RoMeLa are too numerous to call out in the space available, but without a doubt you all were the finest team I could have asked to work with. Even with the press we got I don't think VT fully appreciated the talents we had and how amazing the team was. The fact you all had the faith in my leadership to help me guide the DRC team was incredibly humbling, and I hope I made you guys proud. Not only were you guys amazing coworkers, but you were also amazing friends as well. I hope we have an opportunity to work together again in the future. I do need to mention a few people who specifically helped with the data in this thesis. Dr. Mike Hopkins, Jacob Webb and Coleman Knabe, who helped generate the payload analysis data, Jason Ziglar who led the analysis of computer requirements and perception systems and Jack Newton who helped determine our power requirements. Also thank you to Christian Rippe who was indispensable in the finite

element analysis of the original chest design.

Finally I'd like to thank all the people outside the lab who made me feel at home in Blacksburg. Thank you Ingrid, Chris, Tommy and Charlie for all the dinners concerts and events you invited me to. It's all too easy to get lost in work and the world of robots. You guys always pulled me out and reminded me there was life on the outside.

This work is supported by ONR through grant N00014-11-1-0074 and by DARPA through grant N65236-12-1-1002.

Contents

1	Introduction	1
1.1	DARPA Robotics Challenge	1
1.2	History of Humanoids	2
1.3	History of Inducement Prize	3
1.3.1	DARPA	4
1.4	Chapter summaries	8
2	Literature Review	10
2.1	Previous analysis	10
2.2	Bipedal Walking	11
2.2.1	Humanoids	11
2.2.2	Exoskeletons	14
2.3	Perception	15
2.3.1	LIDAR Mount Types	16
2.4	Power System	18
3	Design	20
3.1	Reevaluation of Requirements	20
3.2	Mechanical Deficiencies	21
3.2.1	Knee	21
3.2.2	Arms	22
3.3	Perception Analysis	22

3.4	Computational Analysis	23
3.5	Electrical Analysis	25
3.6	Simulation	25
3.6.1	Development of the Simulation model	26
3.7	Mass Budget	29
4	Capabilities	30
4.1	Overall Design	30
4.2	Mechanical Design	30
4.3	Perception	33
4.4	Electrical and Computer Systems	33
4.5	Maintenance	34
5	Results	36
5.1	Overall performance	36
5.2	Mechanical requirements	36
5.2.1	Mass Budget	37
5.2.2	Volume	39
5.2.3	Arms	39
5.2.4	Manufacturability	40
5.3	Perception requirements	40
5.4	Electrical Requirements	41
5.5	Maintenance Requirements	41
5.6	DRC Performance	42
6	Future Work	44
6.1	Design Analysis	44
6.2	Knowledge Transfer	44
6.3	Covers	45
6.4	Temperature Protection	45

6.5	Falls and Fall Recovery	46
6.6	Knowledge base	46
6.7	Data Capture	47
Bibliography		48

List of Figures

1.1	Summary of the tasks for the DRC Trials(Source: DARPA)	6
1.2	Summary of the tasks for the DRC Finals (Source: DARPA)	7
2.1	Two competitors from the DRC with extended arm lenth for improved ma- nipulation workspace	13
2.2	Coverage patterns of a yawing and pitching LIDAR mount	17
2.3	Comparison of view from monocular camera and rotating LIDAR	17
2.4	Battery Densities over Time[35]	18
3.1	Comparison of knee torque required to maintain squatting pose of various heights between simulation and hardware testing[48].	28
3.2	Sequence of steps simulated to generate predicted knee torques for ESCHER[48].	28
3.3	Simulated joint torques of a 60kg and 80 kg robot[48].	29
4.1	The computers for ESCHER highlighted in Red	31
4.2	Utem support bushing	32
4.3	Custom mount for hard drive and miniPCI-E boards	34
4.4	Access point for power and data connections for THOR shoulder servo . . .	35
5.1	Finite element analysis of original ESCHER upper body	38
5.2	Timeline for day 1 of the DRC[50]	42
5.3	Timeline for day 2 of the DRC[50]	43

List of Tables

2.1	Humanoid Size Comparison	12
2.2	Exoskeleton Payload Comparison	15
3.1	Benchmark Data for On-board PC Evaluation	24
3.2	ESCHER Sensor Requirements	25
4.1	Comparison of THOR and ESCHER	30

Chapter 1

Introduction

1.1 DARPA Robotics Challenge

The 2005 DARPA Grand Challenge was the first time DARPA used an inducement challenge to attempt to jump start technological innovation. Thanks to the Grand Challenge autonomous vehicle systems have become commercially viable products in little more than a decade. The DARPA Robotics Challenge (DRC) was one of the most ambitious robotics completions ever held attempting to repeat the technological advancements created by the Grand Challenge. Robots have been used by the military for reconnaissance and bomb clearing in increasing amounts since the turn of the century. However these robots have no autonomy and require significant operator training. Many of these systems are unable to climb stairs or open doors and are almost impossible to operate in degraded communications. DARPA developed the competition to help advance robotic technology for use in disaster scenarios where dangerous situations would jeopardize the lives of rescue workers. Success in the DRC required advances in planning, perception, mobility and autonomy to allow general purpose robots to respond to a wide variety of scenarios successfully. The disaster at Fukushima Daiichi nuclear plant shortly before the announcement of the challenge further showed the limitations of the current robots in disaster situations.

Virginia Tech's Team VALOR was a TRACK A team, a team provided with funds to develop a completely new platform from scratch for the purposes of the competition. By the DRC Finals Team VALOR had developed two new humanoid platforms, the Tactical Hazardous Operations Robot (THOR) and the Electric Series Compliant Humanoid for Emergency Response (ESCHER). While THOR was a very advanced platform capable of dynamic force controlled balancing with human like ranges of motion [1, 2] several early design decisions limited its capabilities making it unsuited for the DRC finals. As a result ESCHER was developed with significantly more detailed analysis to ensure its capabilities met the minimum threshold of the DRC Finals. This detailed analysis allowed for the rapid

redesign of over 90% of the systems on THOR producing a robot capable of far more than the DRC required, making it an excellent research platform for many years to come.

1.2 History of Humanoids

Humanoid Robots have long been an aspect of science fiction and popular culture, from Fritz Lang's film *Metropolis* in 1927 to modern depictions of robots in films such as *Star Wars*. However it is only very recently that Humanoids have been able to approach the capabilities of their fictional counter parts. The bipedal form of a human presents inherent challenges in stability since the robot only has two points of contact with the ground rather than three or four. The complexity of actively balancing and Humanoids present a significant challenge to control since they carry significantly more mass in their upper body than in their legs. Why then research humanoids? Traditional robotic platforms take advantage of mechanical systems not available in nature such as wheels or fixed wings. Even many legged robots use a quad or hex legged configuration for additional stability. Much like with humans bipedal gaits can provide several advantages when interacting with the environment if locomotion and disturbance rejection can be made robust. A biped is a holonomic system with a smaller footprint than a quadruped or hexapod. The upright posture of humans allows us to reach higher objects and see at longer distances compared to our ancestors. Similarly biped robots have the potential to interact with a world designed by humans for humans with little change in infrastructure. Additionally a mechanical biped can be used to augment a disabled human in the form of an exoskeleton allowing the to walk and move around the world with more freedom than a wheelchair might allow.

Again, the challenge is robust and reliable locomotion and manipulation. The inherent instability in an upright bipedal posture makes falls potentially catastrophic for humans and robots. The problem of bipedal walking can be modeled as the control of an inverted pendulum, however the processing required for dynamic balancing has limited their performance outside lab settings. The labs that produce the most advanced humanoids today have utilize design techniques based on years of institutional knowledge with little documentation for outside groups to learn from. For new groups attempting to enter into humanoids research it is easy to make mistakes that limit performance and require expensive redesign or even a whole new design iteration.

The first walking humanoid was ELEKTRO, demonstrated at the 1939 World's Fair [3]. He utilized a simple chain drives and flexible shafts in order to move his limbs. ELECTRO had no active control however and depended on his design to remain upright. Significant research began with the development of the concept of the Zero Moment Point (ZMP) by Vukobratović. [4] The ZMP is defined as the location where the contact forces of the robot on the ground are opposite the inertia and momentum of the robots body. By keeping the ZMP within a defined stability boundary dynamic stability of the robot could be maintained. Vukobratović and his team used this research to develop some of the earliest exoskeletons.

Almost simultaneously with the development of ZMP control, mechanical work on bipeds was being performed at Waseda University in Japan. Dr. Ichiro Kato developed several bipeds including the WL-3 and WAP-1 [5] generally considered the first true walking bipeds. These early efforts in bipedal locomotion began to show many of the challenges in size weight and power bipeds faced. All of the early bipeds utilized off-board computing and power for locomotion and it wasn't until WAP-3 in 1971 that full 3 dimensional walking was realized.

These early attempts at bipeds, were purely lower bodies, the development of WABOT-1 is widely considered the first full true full scale anthropomorphic robot. WABOT-1 began to show many of the desired aspects of humanoid robots, with optical and auditory sensors, as well as tactile sensors in the hands for gripping objects. These early attempts still lacked several of the traits desired in a humanoid robot, power tethers and off board computation ensured that these robots would remain lab experiments.

The Honda Humanoid Project started in 1986 was the first attempt to finally create a fully independent biped [6]. Honda's goal with the project was to finally realize the primary advantage of humanoids, their flexibility. In theory a humanoid can utilize human tools and operate in human environments without the need for a purpose built custom solution. The final result ASIMO is one of the first fully realized bipeds to capture the public attention. ASIMO is the first biped capable of running, performing many demonstrations for the general public. However, ASIMO is still operated primarily in controlled conditions. The DRC represented an opportunity to bring robots out of the lab and into the field for disaster response. Many in the humanoids community saw this as an opportunity to demonstrate the utility and flexibility inherent in the humanoid design. A humanoid can utilize the same tools and resources as the disaster response teams minimizing the logistics footprint to accommodate the robot. Additionally, humanoids would have an advantage operating in an environment designed around humans.

1.3 History of Inducement Prize

DARPA's mission statement is to prevent technological surprise to the US and to cause technological surprise to it's enemies. Throughout history Inducement prizes have been used to bolster the state of the art in technology. Since the turn of the century DARPA has used inducement prizes to push the scientific community to advance key technologies. One of the most famous inducement prizes was the British Longitude Act of 1714 to create a method to accurately track the longitude of sailing ships. Several costly shipwrecks caused by imprecise longitudinal measurement drove Parliament to offer a prizes of £10,000, £15,000 and £20,000 for any system that could determine longitude to within 60, 40 and 30 nautical miles respectively. Though researchers at the time were aware that the Earth rotated 15 of longitude per hour no reliable method of measurement existed at the time.

There were two primary methods that rose to prominence, the lunar distance method and

a mechanical chronometer. Early on Lunar distance methods were time intensive requiring up to 4 hours of calculations. Marine Chronometer's weren't even viable technologically until John Harrison created his H-4 marine Chronometer in 1761. Both these technologies advanced their fundamental sciences with the lunar methodology leading to the development of almanacs to cut calculation time down to 10-15 minutes. Chronometers were prohibitively expensive at first, requiring complex bi-metallic springs to compensate for temperature variations, but by 1825 all British ships carried Chronometer's. The ability to accurately navigate the seas the British were able to establish themselves as a naval power despite rivals such as France being already established colonial powers.

The power of inducement prizes to stimulate technological and economic growth has led to their utilization up until modern times. The Ansari X-Prize for example helped drive the creation of commercial space companies. Originally winners were simply trying to bring passengers to the edge of space. However, the success of Scaled Composites in 2004 helped usher in an era of commercial spaceflight led by Space-X. The DARPA Grand Challenge was it's first inducement prize challenge and it's success in accelerating autonomous vehicle technology led directly to the DRC.

1.3.1 DARPA

DARPA is a Department of Defense development agency in response to the Soviet launch of Sputnik in 19h57. DARPA's mission is to prevent technological surprise to the US, and to create technological surprise to our enemies. The most famous development to arise from DARPA is the ARPANET, the first network to implement the TCP/IP protocol, the foundation of the modern Internet. In more modern times, DARPA has pushed research in automation and robotic systems to reduce US troops exposure to dangerous situations such as IED's. DARPA has had excellent results with inducement challenges, the most famous of which was the Grand Challenge. The grand challenge helped accelerate autonomous vehicles from science fiction to legitimate consumer products within 15 years. A similar desire to help boost the utility of robots in disaster scenarios led to the DRC being announced in 2012.

Grand Challenge

In July of 2002 DARPA announced the first Grand Challenge, a 140 mi road race through the desert of California and Nevada. A \$1,000,000 would be awarded to the team who completed the course the fastest within a 10hr limit. The goal was to help reduce the exposure of troops to dangerous situations such as convoy duty in hostile territory. For example in 2003 there were 531 casualties during resupply missions in Iraq, roughly 18% of the total casualties in that year. [7, 8] An analysis of the state of the art at the time predicted half an hour of autonomous driving and a total distance traveled of 2 miles [9]. Of the 15 qualifying teams none were able to complete the challenge. Carnegie Mellon's Red Team achieved the best

performance covering 7.4 miles before being hung up on a rock. [10] To the general public the Grand challenge seemed a failure, however the teams had beaten the expectations of the experts.

The second Grand Challenge was held 18 months later in October of 2005. This time of the 23 finalists 5 vehicles completed the course, including a team created by a Louisiana Insurance company with no prior robotics experience [11]. 22 teams were able to beat the previous best of 7.4 miles. The rapid pace of advancement helped prove the goals behind the Grand Challenge having pushed researchers to bring their project out of the labs and into the field. The Grand Challenge drove significant improvements in perception and localization as well as sensor technologies for field use. The design of the course though physically challenging kept the vehicles in isolation. To truly develop the technologies for full autonomous driving teams would need to operate in real world situations.

To test performance in situation where autonomous and human operated vehicles were operating a third and Final Urban Challenge was held in November 2007. Teams were provided a 60 mi course consisting of way-points and tasks for the teams to accomplish within the 6 Hour time limit. A total of 6 teams completed the entire course with the top 3 finishing within 30 minutes of each other. The design of the Urban Challenge significantly advanced the real time planning and decision making capabilities of autonomous systems.

The advances of the Grand Challenge have led to several modern day autonomous systems. The Google driverless car team is led by Chris Urmson, member of the victorious Tartan Racing team from the Urban Challenge. The Google driverless cars have logged over 1.5 million miles on city streets with only minor incidents and only 1 crash which could be attributed to the vehicle, a considerable improvement over the average American driver's safety record. In the commercial realm, Tesla has added an autopilot feature for use on highways and the Summon capability that allows the vehicle to drive up to 40 ft without a driver for pulling out of tight parking spaces. Within a time span of 10 years the Grand Challenge has advanced the technology well beyond what experts in the field expected and is now seen as an immensely successful government program.

Fukushima and the DRC

The DARPA Robotics Challenge (DRC) was inspired by the events of March 11, 2011 when a large tsunami damaged the Fukushima Daiichi reactors in Japan. The damage caused by the tsunami prevented cooling water from being pumped into the reactor core, causing a partial melt down of the control rods and a dangerous buildup of Hydrogen that led to several explosions. Due to the high radiation concentrations workers were unable to get direct access to the site to assess damage and aid in the cleanup. Attempts were made to use robotic systems to aid in the recovery efforts; however, current systems were unable to navigate through the environment and were unable to significantly contribute to the recovery efforts. As a result DARPA created the DARPA Robotics Challenge in order to accelerate

the development of robotic systems.

The Challenge would be a 3 year event where teams would compete in Trials held in December of 2013 and with a set of finals where teams would compete for a \$2M prize held in 2015. The Trials were used by DARPA to help gauge the state of the art for the Finals resulting in significant changes in the tasks and goals. Teams were divided into 4 tracks. Track A teams received funding to develop a robotic platform and software for the competition. Track B teams were funded to develop software for a Virtual Challenge against unfunded Track C teams. The top 6 teams from the virtual challenge were provided with a Boston Dynamics ATLAS for the competition. Track D teams were any teams who wished to participate.

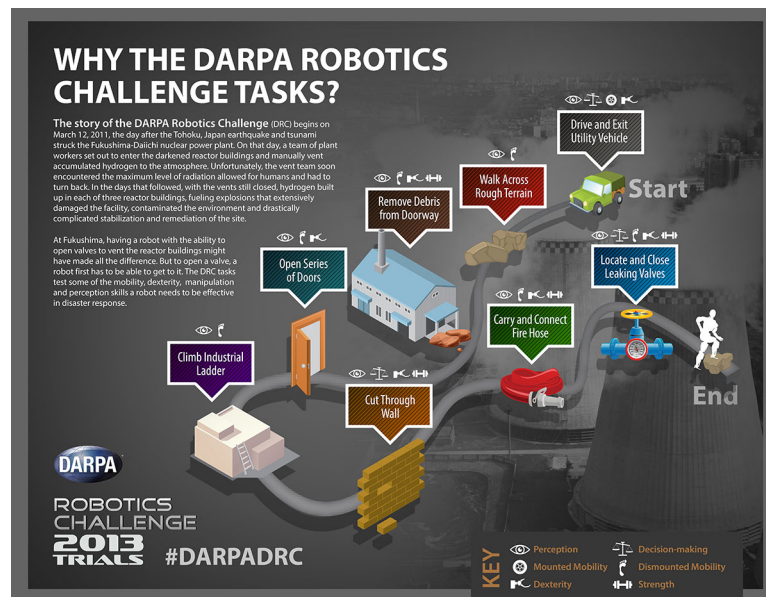


Figure 1.1: Summary of the tasks for the DRC Trials(Source: DARPA)

The DRC trial consisted of 8 timed events designed to simulate the conditions of a typical disaster environment. Robots were given 30 minutes per task and allowed a safety delay and power tether. Communication with the robot occurred wirelessly with bandwidth varied by the minute between “good comms” and “bad comms”. The values during these periods was designed to provide communications similar to 802.111 signals during good comms and that of a cell phone during bad comms. Teams were allowed to intervene and reset a robot for a minimum of 5 minutes penalty. The 8 tasks were:

1. Traverse rough terrain
2. Climb a Ladder
3. Clear debris and walk through a doorway
4. Open 3 closed doors

5. Cut a hole in a wall
6. Open 3 valves
7. Connect and prepare a firehose

The DRC Trials provided DARPA with significant data on the current capabilities of state of the art robotic systems, allowing them to tailor the finals to emphasize development in areas they felt were key in disaster scenarios. The largest change was converting the competition into individual runs on a single course incorporating multiple tasks to be completed. Teams were given an hour to complete these tasks in order to drive the need for more automation and artificial intelligence. In addition, though degraded communication was present during the trials, it still allowed significant teleoperation. In order to drive increased autonomy and improved control efficiency data would be significantly restricted to increase latency and reduce teleoperation when the robot entered an indoor area.

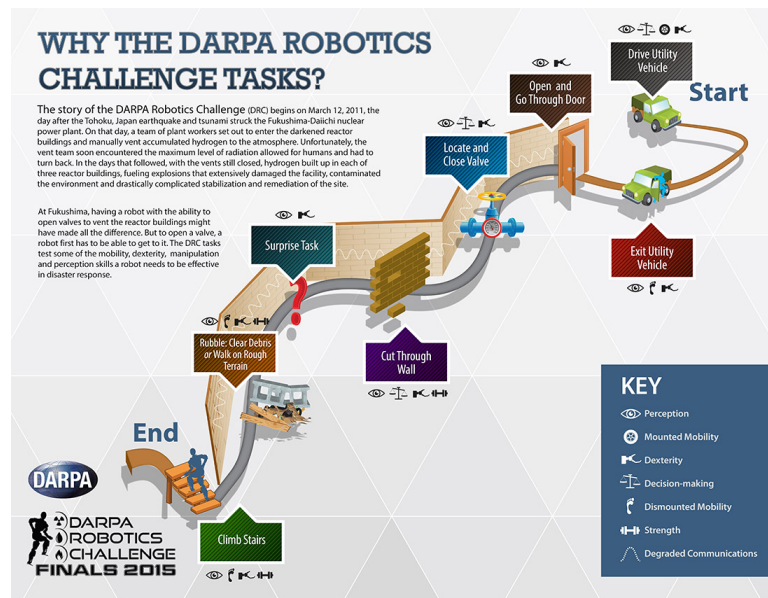


Figure 1.2: Summary of the tasks for the DRC Finals (Source: DARPA)

Figure 1.2 shows the rules for the DRC Finals. To better simulate real world conditions robots would need to operate completely untethered with no safety gantry. Originally no interventions or resets would be allowed, however this rule was later relaxed to allow resets while taking a 10 minute penalty. The teams would need to drive a vehicle 61m and exit the vehicle the open a door to enter the “disaster” area. Upon entry into this area communications would be degraded. Teams would need to turn a valve, cut a hole in a wall using a cutting tool perform a surprise task, then cross rough terrain or rubble strewn terrain and finally climb a set of stairs. Teams had one hour to complete the course and could score a maximum of 8 points.

The goal of the finals was to have fully untethered robots with sliding scale autonomy that could reliably operate in a disaster environment. Many of the 25 teams decided to implement a humanoid design to take advantage of its flexibility in mobility and manipulation tasks. The DRC represented one of the first significant attempts to operate humanoids in the field. Success was mixed, with every humanoid except for the ATLAS from WPI/CMU falling at least once. However, Team IHMC was able to complete all 8 tasks in the finals with a time of 50:26 sufficient for a second place finish and \$1M prize. Team Kaist won the \$2M prize with a humanoid, DRC Hubo, that utilized wheels on its knees and feet for primary locomotion switching to biped movement only when absolutely necessary.

1.4 Chapter summaries

This paper will discuss the development and design of the upper body of the Electric Series Compliant Humanoid for Emergency Response (ESCHER), the Virginia Tech entry to the DRC as Team VALOR. ESCHER was developed on an accelerated 10 month time-line after it was determined that the original platform, the Tactical Hazardous Operations Robot (THOR) proved incapable of completing the tasks required for the DRC Finals. Development of a Humanoid is a complex iterative process that can take many years. Through the use of the techniques outlined in this paper Team VALOR designed built and fielded a system that competed at the DRC and successfully walked 61m across unstructured terrain, a feat achieved by only one other team in almost double the time.

Chapter 2 will survey the field of robotic design. Analysis of both exoskeleton and humanoid robot design will be evaluated to determine how previous efforts achieved the size weight and power requirements of their systems. In addition the overall capabilities of the systems will be compared to what was required of the DRC and what improvements on the designs would be needed to make them able to compete.

Chapter 3 will cover the design analysis of THOR and requirements for the DRC finals. The deficiencies of THOR for the DRC will be discussed and the evaluations of the components for the various subsystems will be listed. The modeling and simulation techniques for estimating joint torques and maximum mass allowed will be discussed. The requirements imposed from the desired sensors and computing power will be discussed.

Chapter 4 will discuss the actual design of the upper body and key features included in the design. Location and final configuration of the various subsystems will be discussed.

Chapter 5 will discuss how the upper body of ESCHER met and exceeded the requirements imposed on it. Key features of the design will be presented and discussed and performance at the DRC will be evaluated.

Chapter 6 will discuss future work and areas of improvement for the team moving forward. Methods for keeping the robot operational and improving performance of the existing system

will be discussed.

Chapter 2

Literature Review

2.1 Previous analysis

Bipedal walking research has primarily taken place in two areas, the development of humanoid robots and in exoskeleton research. Though the systems have different goals many of the same design considerations need to be taken into account. Initial development of bipedal systems focused on the control and development of walking algorithms. Power systems and actuator design utilized off-board augmentation allowing researchers to focus on achieving bipedal locomotion. As algorithms developed computing power and battery power densities increased eventually allowing for these subsystems to be brought on-board into a single self contained systems.

As technology began to enable self contained bipedal systems research in visualization and localization subsystems needed to be incorporated into the platforms. Many of the sensors utilized in modern humanoids research were developed for driverless vehicles in previous grand challenges. LIDAR's are the primary sensors for generating accurate geometric data, while cameras are used to provide visual data to the operators. Currently most LIDAR systems use single or multiple focused beams of laser energy to develop 3 dimensional point clouds, but significant research effort is being placed on wide area flash LIDAR systems the can image the entire field of view simultaneously. Flash LIDAR's have the disadvantage in that they are not suitable for outdoor uses or at longer ranges needed for locomotion. Similarly with the development of the X-Box Kinect [12] and similar structured light sensors has provided low cost stereo vision, but similarly cannot operate effectively in outdoor situations.

As technology advance robotics research platforms have incorporated systems from a wide variety of research areas. The DARPA robotics challenge is one of the first instances where robotic platforms have been forced to operate in an environment designed for humans that is not a controlled laboratory. Not only does this pose an integration challenge in bringing

a wide assortment of requirements to achieve desired performance, but mechanically the systems need to be lightweight and low powered to enable usable operation times. The DRC has helped push research in development outside of perfect lab setting into uncontrolled environments where platform design is a compromise amongst a wide variety of concerns and requirements.

2.2 Bipedal Walking

Though bipedal locomotion is less robust than wheeled or multi-legged platforms it offers some unique advantages over other designs. Wheeled platforms are unable to traverse difficult terrain such as the "knee knockers" around the hatches in a Navy ship or stairways. Multi legged robots have a larger footprint that can make maneuverability difficult and tend to be lower to the ground potentially making manipulation difficult. The world is designed around the human form and such bipedal humanoids will have utility in a larger range of situations. Unfortunately bipedal designs require constant active control to remain balanced and upright. A fall due to a momentary error can be catastrophic. The rules for the DRC finals were structured to push teams into situations that may not have been directly planned for. Though none of the bipeds in the DRC were able to recover from falls, Boston Dynamics has since shown fall recovery capabilities in the latest generation ATLAS robot.[citation] Additionally, team WPI-CMU was able to score 7 out of 8 points in the competitions without suffering a fall in 3 attempts. Though a final solution is still unavailable, competitions like the DRC will help bring bipeds to their full potential.

2.2.1 Humanoids

Modern humanoid designs derive their designs from the environments in which they wish to operate. With bipeds this is typically in human environments resulting in size and weight requirements in roughly the human range. Table 2.1 shows a comparison of several humanoids designed since the year 2000 compared against the Hybrid III crash test dummies that mimic a 50th Percent Male. Traditional designs of humanoids have been actuated by either electric or hydraulic actuators. Electric Humanoids have tended to be smaller to the the lower power to weight ratio of electric motors versus hydraulics.

Early humanoid designs attempt to maintain human proportions and joint configurations. This provides an easy initial design metric but may not necessarily provide the optimal design. For example the human wrist is a 3 Degree of Freedom(DoF) joint packaged in a very small area. Modern motor technology does not allow for a 3 DoF wrist to be mechanically packaged in the same area significantly changing the workspace of the end effector. More of the forearm will be taken up with actuators resulting in the need to change the proportions of the arms. Similarly the difficulty in the design of flexible feet for robots means that certain

Table 2.1: Humanoid Size Comparison

Name	Year Created	Mass (kg)	Height (cm)
Honda P2[6]	1998	210	182
HRP-2[13]	2002	54	155
HUBO(KHR-1)[14]	2002	48	120
Honda Asimo[15]	2007	43	120
Wabian-2[16]	2006	64	153
Lola[17]	2009	55	180
ATLAS (Gen 1) [18]	2013	155	188
DRC-HUBO[19]	2013	52	147
Hybrid III (Human Male)[20]	—	78	175

motions, such as picking objects off the ground, are more difficult. This often drive larger ranges of motion in the ankles of robots than in humans. As humanoids have moved out of the lab and into the field practical design considerations have resulted in less human like proportions as demonstrated in Figure 2.1

Actuator Selection

Most electric humanoid designs utilize rotary actuators for each degree of freedom. Power to weight ratio is one of the largest design considerations for actuators. DRC Hubo designed by researchers at Korea Advanced Institute of Science and Technology (KAIST) is an upgrade of previous Hubo designs specifically to address the challenges of the DRC. Key to the acutator design is the reduction of backlash to reduce errors for the motion control system. This drove the use of Harmonic Drive gearboxes for their near zero backlash properties driven by electric motors attached via belt drive [21]. Brushed motors driven at 24V were used for the improved thermal properties versus brushless motors. Joint torques were selected based on prior experimentation, a technique dependent on prior existing systems for improved perfomance against known metrics. This can pose a challenge when designing a system without prior knowledge.

Hydraulic linear actuators have been used sparingly in robotics such as the WL-12 family developed at Waseda University [5]. The danger and difficulty of hydraulics in a lab setting likely limited their use. However with the desire to move into field operations hydraulic actuators have become more prevalent. Quadrupeds such as Big Dog by Boston Dynamics utilized hydraulic actuators for their power to weight ratio and dynamic response. These actuators could be implemented in a series elastic configuration [22] to achieve improved energy efficiency and low pass filtering. These actuators were implemented on Boston Dynamics Petman, the precursor to the ATLAS. Linear actuators can present a packaging challenge, but can provide excellent power to weight ratios. Even when configured for electric drive, the ball screw actuators of THOR can provide 2000N of force for 0.938g [23]. The

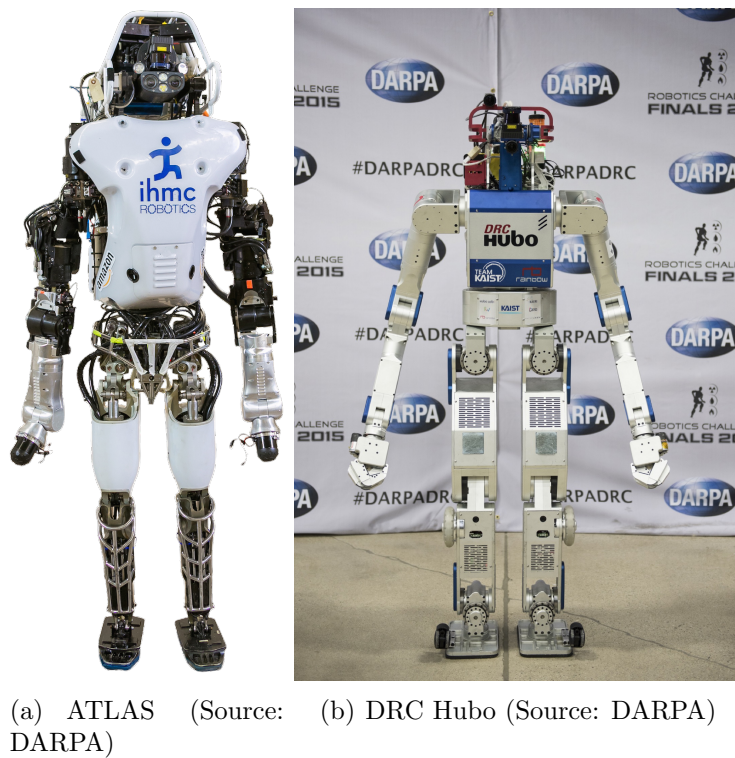


Figure 2.1: Two competitors from the DRC with extended arm lengths for improved manipulation workspace

packaging for the linear actuators allows them to align quite well with the limbs of a robot, though the need for a lever arm to drive the joints can cause interference with covers.

Force sensing is becoming increasingly important for locomotion of bipeds. Traditional walking algorithm using position control depend on detailed knowledge of the terrain being traversed. Whole body control using force control of the actuators was proposed by Dr. Jerry Pratt for the biped Spring Flamingo. [24] With accurate modeling and force sensing an optimized controller can be used to generate a walking trajectory and reject disturbances. Rotary actuators typically use current sensing for force control. While simple to implement required accuracy can be difficult to achieve. Linear actuators can directly mount load cells in-line with the output shaft providing direct force measurement. This direct force measurement coupled with a joint encoder provides highly accurate joint torque measurement. This whole body force control technique was successfully implemented by Team IHMC at the DRC led by Dr. Pratt [22] as well as on THOR by Dr. Mike Hopkins [1]

Motor selection has often utilized prior experience and simple simulation. The design of LOLA from Technische Universitat Munchen utilized an in house simulation model that not only modeled the larger dynamics of the system but modeled the motors as well. [25] While the results were promising developing a custom simulator is time consuming and difficult. Other designs, such as Hubo or HRP-2 iterated on previously successful designs and experience. Developing a novel biped in a short period of time requires simpler tools and methods for generating the desired joint torques during the design phase.

2.2.2 Exoskeletons

Exoskeleton design faces many of the same issues as the design of humanoids. Most exoskeletons for rehabilitation are focused on the lower body only, allowing for a greater overall payload. This is offset by the challenge of having to be worn by a human pilot. In addition to power to weight motor selection must take into account actuator volume to prevent the volume of the exoskeleton becoming too large to be practical for day to day use. Additionally exoskeletons can operate in two regimes of performance, human augmentation and rehabilitation. Human augmentation assumes a healthy pilot who can support himself, a rehabilitation exoskeleton will have a pilot with limited mobility, requiring the exoskeleton to support the pilot's weight. Payload capacity is one of the driving factors in the design and implementation of exoskeletons. Many rehabilitation exoskeletons will only actuate two of the joints in the leg, the hip and the knee, while the operator supports their weight using walking sticks or railings. Additionally many exoskeletons are designed for flat terrain walking which requires less torque from the actuators, still the techniques used in actuator selection can inform the design of bipedal robots.

The Berkley Lower Extremity Exoskeleton or BLEEX analyzed the human walk cycle extensively to determine the power and torque requirements of the lower body during a human walk cycle and during ascending and descending stairs. [26] The Hydraulic actuators

Table 2.2: Exoskeleton Payload Comparison

Name	Year Created	Payload (kg)
Bleex[26]	2004	34
HAL-5[27]	2004	80
HULC[28, 29]	2008	90

on BLEEX were sized given a constant hydraulic pressure to provide the necessary joint torques and speeds for the desired walking velocity with a 10% factor of safety being added on top of the calculated requirements. The original BLEEX used approximately 2.3 kw when walking due to its hydraulics, since then most exoskeleton systems use electric motors.

While BLEEX Provides insight into base level requirements for human motion the lack of actuation on 4 of the 6 DoF in the legs makes it difficult to determine requirements for those joints in a biped. Additionally the ability to utilize a flexible toe and active human pilot means that the walk cycle of an exoskeleton will be slightly different than that of a humanoid. The lack of a toe increases the required range of motion and torques in the ankle and knee during stair and terrain climbing. The differences in Human and Robotic gaits though small is significant enough to merit consideration during the design of a humanoid.

2.3 Perception

There are three primary sensor types typically used for robot perception on autonomous vehicles. Many of the sensors considered for the DRC were first developed during the DARPA Grand Challenges for autonomous driving. The perception system should transmit information to the operator to allow navigation as well as geometric data to generate a map of the environment. Combining the geometric data with accurate position estimates advanced techniques such as Simultaneous Localization And Mapping (SLAM) [30] and obstacle avoidance and path planning can be implemented.

The primary sensor system for the operator is typically some form of visual camera. The original THOR mounted a Proscilica GT-1290 monocular camera. The monocular camera provided useful feedback to the operator but no geometric data. Stereo camera setups can use a variety of techniques to generate depth information from standard images. The typical limitations for these systems is bandwidth for example the Carnegie Robotics MultiSense S7 can generate 120 MB/s of data. At 2048x1088 resolution this corresponds to a frame rate of 7.5 FPS. This low frame rate makes direct teleoperation difficult even without any latency that may be introduced into the system. Stereo camera systems are used on a wide variety of humanoids such as the Boston Dynamics ATLAS or the NASA Valkyrie [18, 31]

LIDAR's are the typical sensor for accurate long range measurements. LIDAR's can provide

large amounts of low noise three dimensional data at distances of 30-50m at low data volumes. LIDAR's can be configured in single and multi laser configurations with varying fields of view as well as in a flash or pulsed configuration. Mounting of a LIDAR can be critical in accurately determining the geometry of an object as the arrangement of the lasers can cause features to be missed. Most LIDAR's will be actuated in order to help eliminate these performance gaps. LIDAR's were present on every robot competing in the DRC in a variety of configurations.

Structured light sensors have become more common in robotic systems with the development of the Microsoft Kinect. Structured light sensors project a known light pattern which is then interpreted by the cameras to produce a reconstruction of surface shapes. While structured light sensors can provide an extremely low cost high quality point cloud, their dependence on an infrared image pattern makes them unusable in sunlight or other high infrared environments. Though ineffective in outdoors situations, many research robots such as the PR2 from Willow Garage [32] or the DRC-HUBO [19] use structured light sensors for indoor geometry detection.

Sensor placement is driven by field of view and reaction distance. For autonomous vehicles multiple sensors may be necessary to cover the full environment around the vehicle. Similarly the high speeds of the vehicles require a larger view distance to allow for processing and reaction times. Humanoids which traditionally require some form of manipulation will have minimum distance constraints. For Stereo sensors minimum distance will be driven by the separation between the cameras. Similarly, LIDAR systems have a minimum range that is typically on the order of tens of centimeters, though this can often be compensated for through proper positioning. Most humanoids mount primary sensors on the head to allow for pan - tilt motion. This allows for repositioning sensors to improve feedback during manipulation

2.3.1 LIDAR Mount Types

LIDAR systems will typically transmit in a vertical or horizontal plane . This will produce a fan pattern that spreads the greater the distance from the emitter. In order to build 3D information the system must be actuated to sweep the data and build a point cloud. As demonstrated in Figure 2.2 the pattern produce will create bands where no information is measured. It is important when selecting the axis of motion to be cognizant of desired of geometries which may be important to observe. For example in 2.2(b) the sweep pattern has the potential to miss horizontal edges of thin objects such as shelves or door handles. Rotating can help alleviate this effect at the cost of mechanical complexity. Rotating multi laser LIDARS like the Velodyne PUCK [33] are generally fixed with no actuation making them an ideal sensor; however, before the release of the PUCK their size and weight made them difficult to mount on humanoids.

Figure 2.3 shows a comparison between a monocular camera and a 32 laser rotating LIDAR.

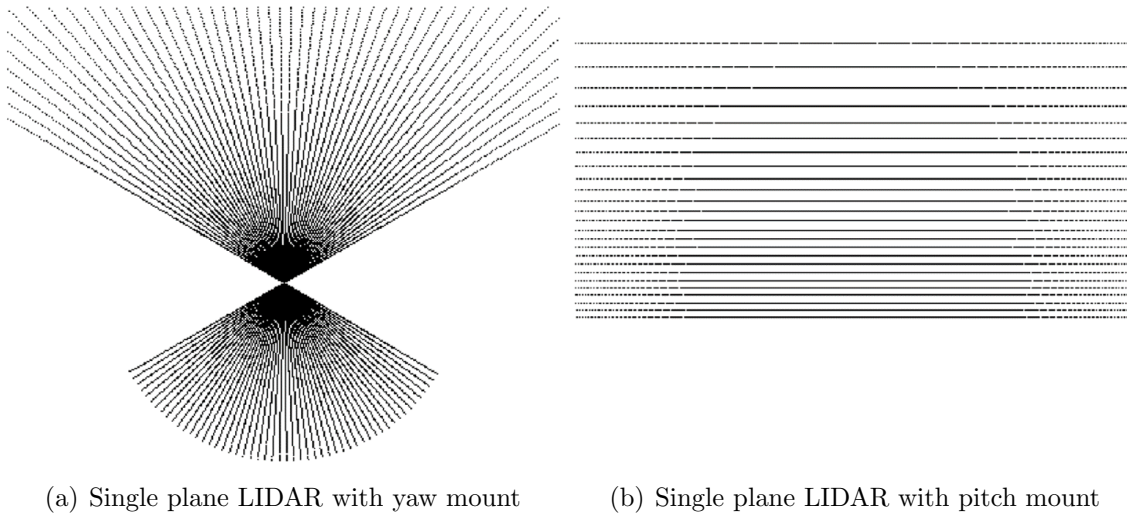


Figure 2.2: Coverage patterns of a yawing and pitching LIDAR mount

2.3(b) shows the distinct horizontal bands corresponding to each of the 32 lasers are created by the vertical fan arrangement of the sensors. Features parallel to these bands that are easily visible in 2.3(a) such as where the floor meets the wall, the power outlets and top of the box have significant uncertainty. If the Velodyne were rolled or wobbled, data points could be taken between the bands. While this would lower horizontal data resolution overall more geometry details can be estimated.

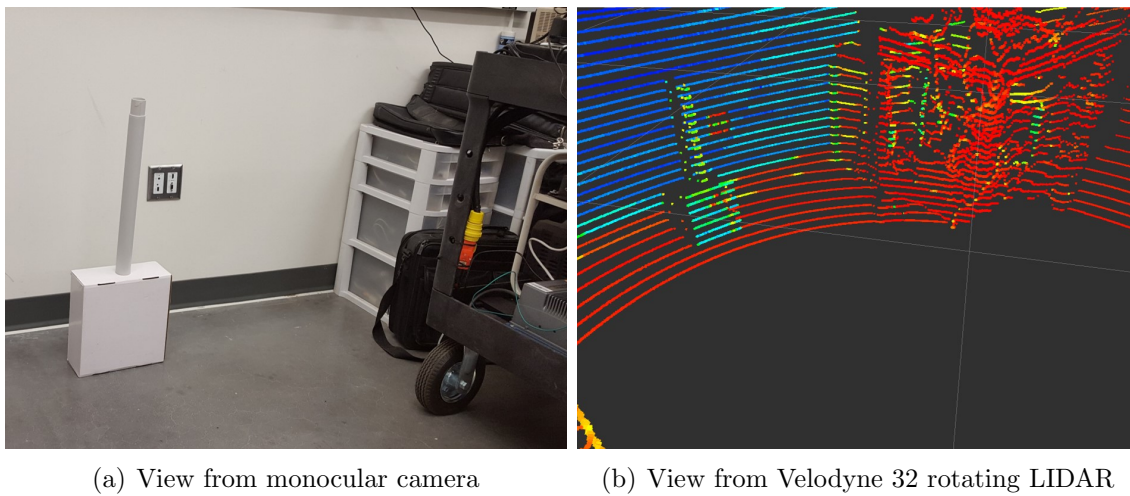


Figure 2.3: Comparison of view from monocular camera and rotating LIDAR

2.4 Power System

Power systems continue to be one of the limiting factors in Bipedal walking performance. Early humanoids used off-board power systems to to achive locomotion since battery technologies hadn't achieved the power densities required for adequate on-board performance. As battery, motor and computer technology improved Humanoids became untethered from the wall and were finally able to move to fully untethered operations. As shown in Figure 2.4 the energy density of batteries has increased with the advent of portable electronics. Additionally improvements in mechanical efficiency of motors has made gas power potentially viable in certain applications. BLEEX, the exoskeleton developed at University of California Berkeley utilizes gas powered motors to supply the 3 HP necessary for locomotion [34]. Batteries still remain the primary method for providing power however since most systems are required to operate indoors.

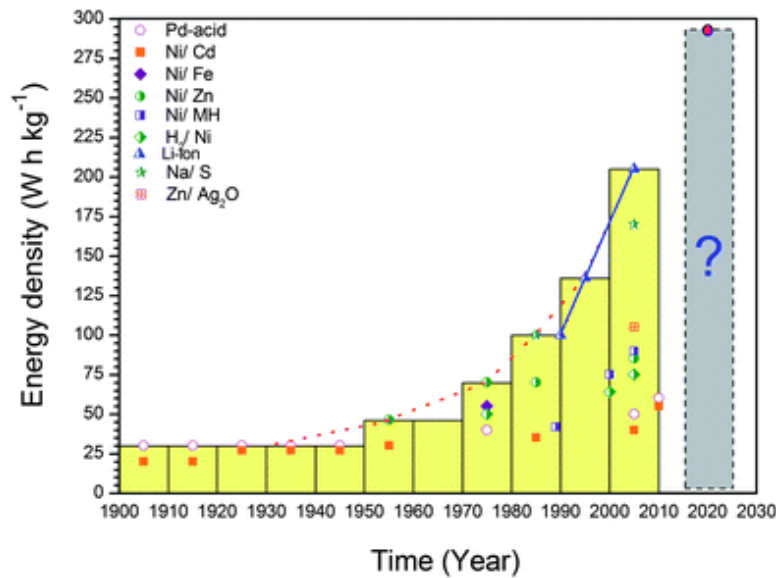


Figure 2.4: Battery Densities over Time[35]

Towards the end of the 1990's research at Honda had produced a traditional humanoid with its P2 robot [6]. P2 utilized 20 kg of NiZn batteries which have an energy density of roughly 100 Wh/kg for a total of 2000 Wh of battery power. Given its stated battery life of 15 minutes this is approximately 8000 W of power consumption. P2 had 26 DoF controlled by a PC and 4 Micro SPARC II Micro processors. Locomotion consumed 3kW driving the short battery life. By the time HRP-1 was developed in 2000 by Dr Inoue [36] robot mass and walking efficiency had improved, HRP-1 had a mass of 120 kg and consumed 1 kW while walking, allowing for over 30 minutes of operation on NiZn batteries. [37]

As Lithium Ion batteries became more prevalent in cell phones and laptop computers their use began to spread into humanoid and exoskeleton development as well. Though various

formulations of Lithium Ion batteries exist, their power densities DRC-Hubo utilized Lithium Ion battery packs have an energy density of between 100-265 W*h/kg. This provides far better efficiency per mass which coupled with improvements in actuator design and processing efficiency have allowed for longer run times for less mass. Modern Humanoids typically utilize Lithium Polymer (LiPo) batteries. The cell voltage of 3.3V per cell and rapid charge capabilities of 1-5 C make them ideal for applications where weight is a concern. For KHR-3 designed by Dr. Jun-Ho Oh proper battery selection drove the selection of the drive motors for the actuators [21]. The higher the voltage required the more battery packs that need to be wired in series in order to provide the desired bus voltage, but the lower the current needed to produce equal torque. As a result of space constraints KHR-3 utilize a 20 Ah 24v LiPo battery pack, typical Batteries of this class would have a mass of ~ 3 kg or $\sim 5\%$ of the total 55 kg weight of KHR-3.

Assembly and design of battery packs can have a strong influence on overall battery volume as well. Flat battery cells will pack together with little space in between the cells as opposed to a cylindrical cell configuration. Care must be taken with Lithium polymer batteries to allow for some extra space for expansion of the battery. Small amounts of gas can build up due to the slight vaporization of the electrolyte layer. Since LiPo batteries often do not have a rigid case the pack will swell slightly. Proper care and maintenance of the battery packs will keep this swelling to a minimum. LiPo batteries must also be protected from puncture or short circuit as this can result in a dangerous exothermic reaction that can destroy the platform.

Care must also be taken to provide sufficient power for instrumentation. DC-DC conversion will create inefficiencies and requires large converter boards. This can be especially problematic with high current draw systems, such as computers which often run at a non standard voltage. Often times it can be more efficient to have a separate battery bus using lower voltage batteries for instrumentation and computing buses.

Chapter 3

Design

3.1 Reevaluation of Requirements

While THOR was an excellent technology demonstrator for Series Elastic Actuators (SEAs) and Whole Body Control, it could not meet the requirements of the DRC Finals. The original analysis used for the design of the knee used static loads based on the prototype legs to calculate required joint torques. The 100% factor of safety used proved to be too low for stepping over an obstacle greater than half an inch in height. During the redesign period for ESCHER THOR had yet to walk leading to concerns that even locomotion could prove to be beyond the systems capabilities. Simulation and analysis was used to determine new joint torque requirements and an overall maximum mass for the robot.

The original design of THOR was also deficient in its perception and computer systems. While ZMP force control balancing was possible using a low power dual-core i7 processor, the whole body controller utilized almost the complete processing power of a desktop with a 6-Core 3.3 Ghz i7 in simulation. Additionally sensor analysis determined that the perception system would need to be upgraded with a new stereo optical system and an improved IMU to enable localization techniques. Increased perception capabilities further drove computer selection which in turn drove power system design.

The various trade studies undertaken for the design of ESCHER placed stringent requirements on the upper body. Structural mass was significantly limited to allow sufficient margin for climbing stairs and rubble, and volume could not increase significantly to allow transitioning through the door. However by performing the analysis of all the various systems and leaving sufficient margin there was high confidence in the ability of ESCHER to meet all the DRC tasks. Once the physical system was assembled the extra margin resulted in a system far more capable than its design requirements.

3.2 Mechanical Deficiencies

As described by Bryce Lee and Coleman Knabe [2, 23] THOR utilized custom linear SEAs in its lower body to achieve force controlled locomotion. The proof of concept for this design was the original SAFFiR prototype legs designed by Dr. Derek Lahr and Lee which was able to walk on a wide variety of surfaces with no perception systems beyond its force sensors. These prototype legs lacked the range of motion required for the tasks of the DRC leading to Lee's design of THOR.

To determine the required joint torques a static analysis using the masses and joint lengths of the prototype legs. The legs were placed in a squatting position to represent the worst case of the robot needing to pick up an object from the ground. The calculated joint torques were then doubled as a factor of safety. These joint torques required a redesign of the linear SEAs for increased force output. Knabe decided to implement a 4-bar Hoekens linkage to achieve the desired range of motion with the side effect of producing an almost linear power curve through the entire range of motion [38]. Once the system was implemented in hardware, testing proved that this design was inadequate.

3.2.1 Knee

The Hoekens linkage used on THOR's knee has some very useful properties mechanically. The linear power curve allows for a large torque at the extremes of movement. However this sacrifices the peak torque in the center of the range of motion. The original assumptions predicted that holding a squatting position would generated the highest joint torques. Analysis however revealed a twofold problem, bandwidth in the actuators was significantly reduced at high torques, and even normal walking required torques above the continuous range in the center of the range of motion.

The simulation developed for testing of the whole body controller provided near real-time dynamic simulation of THOR. A simulation environment was created to test the joint torques required to move the robot across a basic course which featured a 9 in step representing the stair climbing task for the DRC finals. The mass of the robot was kept the same with torque limits removed for testing. Simulation showed a peak torque of 195 Nm at a joint angle of 110 in the knee joint. The peak torque of the Hoekens linkage driven knee could generate a peak torque of 115 Nm at crank angles of 25 and 125. The continuous torque available for THOR's knee is only 40 Nm, meaning even small steps onto objects were beyond the continuous operation area of the knee. Given the 50% duty cycle of stepping the motors would rapidly overheat causing a failure in the system.

Additionally as demonstrated in testing by Dr. Viktor Orekhov [39] showed a significant change in bandwidth available based on the input force amplitude. Operating outside the bandwidth range degrades the assumption that the actuator is operating as a pure point

source. The bandwidth of the THOR SEAs can vary from 60 Hz at a 50 N input amplitude to 11 Hz at 800 N input amplitude. The desired force bandwidth of the SEAs was roughly 40 Hz which corresponds to roughly a 100 N input amplitude. Any obstacle pushed the actuator outside its continuous operation range of 685 N, significantly reducing the available bandwidth.

3.2.2 Arms

The original arms utilized by THOR were composed of ROBOTIS Dynamixel Pro motors. The arms were arranged in a 7-Degree of Freedom (DOF) configuration. The wrist was arranged in a roll-yaw-roll configuration and the end effectors were custom 2-DOF under actuated grippers [40].

The ROBOTIS motors had an excellent power to weight ratio with an 857g 200W servo providing 39 Nm of continuous torque. The total mass of the arms was 6.6kgs providing a payload capacity of 2.2kgs. While the arms were a simple low cost solutions they presented several disadvantages for operations. Though the servos themselves are continuous rotation the external wiring limits the actual range of motion on the arms. The continuous movement of the wiring harnesses led to significant maintenance issues and often required a complete replacement. The roll-yaw-roll configuration of the wrist significantly reduced the workspace of the arms, allowing the potential for gimbal lock. Additionally their mounting position and length meant the robot would have difficulty operating a doorknob due to its position in the workspace.

3.3 Perception Analysis

The original Perception system for THOR utilized a fixed monocular camera and 2D scanning LIDAR mounted in the head and a similar LIDAR mounted on the chest in a yes/yes configuration. With the redesign of THOR time was taken to perform a more thorough analysis of sensors for the revamped DRC Finals.

Three primary situations were identified for sensor selection, Walking, Autonomy and Human Machine Interface (HMI). Each of these conditions placed certain requirements on range and accuracy for the sensors. Primary drivers were sensor range during the rough terrain course and driving resulting in a desired maximum range of over 3.6 M while manipulation required sensors to operate at less than 0.8m. Sensors needed to provide appearance and geometric data and would need to operate in a bright outdoor environment as well as smoke/fire environments. The goal was to have a system capable of 6D Simultaneous Localization and Mapping (SLAM). [30]

After analysis of a mixture of optical and LIDAR sensors the decision to mount a Carnegie

Robotics Multisense S7 with a rotating Hokuyo LIDAR for the DRC augmented with two FLIR A35 infrared cameras for firefighting applications. The chest LIDAR mounting points were kept, but would only be utilized if time allowed the integration of the data into the system. In order to determine geometric data the head LIDAR would be attached to a servo allowing variable sweep rates. Geometric analysis was performed to choose between yaw pitch rolling and a wobbler mounts. While wobbler mounts offer a very desirable coverage pattern combining yaw and pitch, the mechanical complexity would be difficult to fit in the head. Single axis motion was evaluated, but presented geometry problems. Yaw only motion can miss vertical features such as door frames or corners. Pitching the LIDAR can miss horizontal features like shelves or certain door handles. A rolling motion was determined as optimal, frequency could be easily varied to improve feature resolution and the rolling motion created a foveated effect where the highest level of detail was in the center of the field of view.

A Multisense S7 stereo head replaced the Proscilica GT-1290 to provide both geometric data and visual data for the operator. By combining this with the rotating LIDAR ESCHER would have a similar configuration to the ATLAS the Track B teams would be competing with. Unlike the ATLAS however, the head yaw and pitch axes would be kept in order to allow the operator a greater field of view. With the development of improved perception the traditional flexible mounting system for attaching the Robot to its safety gantry would need to be changed to a fixed frame so that an exclusion template could be added to the software. Without this template the robot would think it was too close to an obstacle to safely move and remain motionless.

3.4 Computational Analysis

The momentum control system designed by Dr. Hopkins [1] for the DRC was a custom designed architecture written in the programming language Lua. A scripting designed to function as a shell around other programs Lua is unable to utilize multiple computer cores. The intense PC's originally used for THOR proved unable to run the motion system, requiring an off-board computer running at 3.3 GHz to successfully balance the robot.

Computing power was primarily driven by the motion system, but sufficient overhead was needed to run the Perception and manipulation systems as well. Traditionally predicting the necessary computing power for a project has been difficult, research papers often neglect the computing power required for an algorithm, such as SLAM. Additionally, a wide variety of factors such as programming language, code efficiency and capacity for parallelization and multi threading will affect processing time. Also driving the minimum desired computing power Team VALOR entered a partnership with Team VIGIR for the DRC finals to share their software based on ROS designed to run on the Boston Dynamics ATLAS. The ATLAS had a single i7 Processor dedicated to motion, with two more available for the track B teams to develop their custom software. Three i7 processors was considered a minimum to ensure

compatibility with the software from team VIGIR.

At least one of the computers would also need two Ethernet ports to allow the Multisense S7 and a network connection to be used simultaneously. The computers must be able to add cards for CANBus control with a minimum of 4 CAN channels available for the motion system. CANBUS has significant bandwidth degradation when the number of devices is increased. To maximize bandwidth each leg was given a CAN channel, and the force torque sensors in the ankles were given their own channel. The 4th was left open for future upgrades. With the addition of the Adroit arms which utilize CAN, ESCHER was eventually required to use 5 total CANBUS channels.

Nine small form factor computers were evaluated as potential candidates. One of the primary limitations was the inability to run compiled code or to take advantage of multi-threading for the motion control system due to LUA. Processors with high clock speeds were desired since the motion system would need as much single-thread speed as possible. The list was narrowed to 3 machines due to requirements for external connectors for the various perception systems. In order to attempt to predict performance the rate of the control loop for the motion system was evaluated on a variety of systems as a benchmark. A set of 1 Brix and 2 ADL QM87PC's was ordered for testing and integration on THOR with the option to pursue the Intense PC 2 as a platform if cost became an issue.

Table 3.1: Benchmark Data for On-board PC Evaluation

Computer	Processor	Clock Speed (GHz)	Motion Control Loop (Hz)
Intense PC	Core i7-3517UE	1.7 (2.8)	75
Development Desktop	Core i7-3960X	3.3 (3.9)	300
Brix Pro	Core i7-4770R	3.9	250
ADLQM87PC	Core i7-4700EQ	3.4	214

After testing on THOR final selected configuration of 2 Gigabyte Brix Pro computers and two ADL QM87PC's was determined as optimal for ESCHER. The Brix computers provided fast single threaded processing at 3.9 GHz in turbo mode at the cost of high power consumption. The ADL PC's use the PC-104 standard form factor, and are lower power, while still providing high speed at 3.4 GHZ. Both machines feature 4 core i7 processors, with 2 threads per core. Performance running the motion system was predicted using the dynamic simulation developed in Gazebo [41]. As shown in Table 3.1 the Brix's provided an estimated 250 Hz and the ADL's an estimated 214 Hz. The minimum desired speed was 200 Hz though ESCHER was able to function at speeds as low as 150 Hz. For connections the Brix's feature 2 mini-PCI-e ports for CANBUS adapters and the ADL machines could optionally mount two Ethernet ports. The additional computing power came at a cost to power consumption raising maximum computer power consumption from 36w to 276w.

3.5 Electrical Analysis

With The significant additions in both sensor and computing power the electrical system for ESCHER had to be completely upgraded from THOR. For the DRC finals runs were extended to 1 hour. Adding in setup and take down time a minimum of 75 minutes of run time was desired. Worst case power was determined using the maximum potential sensor and computer load-out. This included sensors like the additional Hokuyo LIDAR and Point Grey camera to allow for some potential growth. Total power was estimated at 90 w.

Table 3.2: ESCHER Sensor Requirements

Device	Quantity	Power Draw per Device (W)	Device Power (W)
Multisense S7	1	20	20
Hokuyo Lidar	2	12	24
Pointgrey Firefly MV	1	1	1
Flir A35	2	2.5	5
UV Sensor	1	1	1
Microstrain IMU	1	0.4	0.4
Extremis AHRS	1	0	0
Force/Torque Board	2	6	12
Scourge	2	2.4	4.8
Futek Load Cell	12	0.36	4.32
Motorslug	6	1.75	10.5
8 port switch	1	7	7
Total:			90.02

Power consumption of the computers was estimated at 276 W for a total of 366 w for bus and computing power. Get walking info from Jack. When adding in the power for the locomotion system a total worst case power consumption was set as 516 w. A factor of safety of 100% was used to allow for growth and to prevent overly draining the batteries and preserve their health. A final decision was made to use 4 25.9V 22,000 mAh Lithium-Polymer Batteries from Max Amps as the power source for ESCHER. Each of these batteries has a mass of ~3kgs meaning the batteries alone would be the equivalent of 20% of THOR's mass. New power distribution boards would need to be designed for ESCHER and space would need to be allocated to mount the new board known as the Thunderlane.

3.6 Simulation

Simulation featured heavily in developing the overall requirements for ESCHER. Gazebo, an open source dynamic simulator was used during the development of THOR and ESCHER. Gazebo was used to predict that THOR would not be able to complete the DRC Finals,

a prediction eventually verified using hardware testing. By using the simulation to model predicted performance of ESCHER a maximum payload based on a dual actuator knee configuration was determined.

3.6.1 Development of the Simulation model

Simulation was vital to the development of the Whole-Body Control system on THOR and ESCHER. To calculate the center of mass accurately a detailed knowledge of the various joint inertias was required. Minimizing error in the CAD model that was under constant development required not just accurate modeling, but version control and the incorporation of software best practices to ensure the control systems team was always using the latest data. Using a simulated test course joint torques required for the DRC finals rough terrain and stairs could be accurately predicted to give a design envelop.

Creation of the CAD model

Dynamic accuracy of the model is strongly dependent on the accuracy of link inertia definitions. For both THOR and ESCHER models, individual link inertias are generated from a detailed CAD model built in Siemens NX. Each component on the robot is modelled using a custom density calculated from the part's measured mass and CAD volume. However, CAD model does not include wires or wire weight, so defined body link masses of the simulation model are increased proportionally in the head, chest, and legs to match the overall hardware mass. For the initial design of ESCHER, a mass margin of 10% was allowed and distributed over the body. This method is easy to implement, yet is sensitive enough to model mass distributions and moments of inertia without requiring experimental identification of inertial parameters or link dynamics.

In order to maintain a known “good” version for the controls team while development of ESCHER continued techniques from the realm of software were incorporated into the development process. Version control software, GIT, was used to store the CAD model. Any development occurred on branches for specific parts to avoid modifying the master branch from which all controls data was generated. Branches could only be merged into the master branch when a team member formally issued a pull request. A team member would be randomly assigned to verify the modifications adhered to both directory structure and file naming conventions. Files would also be checked against agreed upon CAD guidelines for display clarity and constraints. Only when verified by a second team member would the model be updated in the master branch.

Gazebo

For the DRC the team used Gazebo as its simulation tool. An open source ODE solver, Gazebo allowed for the simulation of a wide variety of environments for testing and development purposes. [41]. Balancing the fidelity of the model between accuracy and performance was critical to providing timely analysis.

The joint torques are measured from the in-line actuator load cells, converting from force to torque using a quasi static assumption. This model holds due to the ability to approximate the actuators as a pure torque source [42]. This rigid body model with ideal torque sources is a common technique for modeling torque controlled robots [43, 44, 45, 46, 47].

Verification of Data One of the challenges when utilizing Gazebo is difficulty in achieving convergence in the ODE when there is a large disparity in the masses between two linked bodies. The trunnions utilized in the universal joints of the ankles and hips were the largest sources of the numerical instability. To solve this problem the smaller mass, the trunnions, were increased in mass in the model with an equivalent mass subtracted from the larger link. This was performed until the ODE converged properly. While this method did introduce small errors experimental testing showed performance was still acceptable [48]

A second validation experiment was conducted with THOR to compare the torque modeling of the simulator to measurements on hardware. The robot center of mass (COM) was commanded downward to squat at varying heights, using the whole-body controller developed by Hopkins et al. [49], and the required knee torques to maintain the height of each static pose were recorded. Figure 3.1 contains the required knee torque across a range of hip joint heights from simulation and hardware testing. While this test only covered static cases, the simulated torque prediction tracked closely with the hardware data, furthering confidence in the accuracy of the simulator model for dynamic scenarios.

Hardware testing of THOR consistently overloaded the knee joint while stepping up onto objects similar to that shown in Fig. Figure 3.2. Simulation of THOR in Gazebo revealed that stair stepping approached peak torque limits in the hip pitch and surpassed them in the knee, as shown in Fig. Figure 3.3. With the additional hardware requirements for the upper body a redesign of the knee and lower body would be necessary. The validated Gazebo simulator derived hip and knee pitch torque and power requirements for the ESCHER thigh redesign. The THOR model was modified to vary it's total mass and placed on a simulated track that required a worst case step of 23cm, shown in Fig. Figure 3.2. Over all mass was varied in 5kg increments from 60kg to 85 kg.

Joint positions, velocities, and torques were recorded for each mass increment were used to determine the critical joint angles requiring maximum torque. Fig. Figure 3.3 contains joint torque data from the 60kg and 85 kg tests. From this data, the new hip pitch joint should support a peak torque of 130 Nm at -85 deg, while the knee joint should support a peak

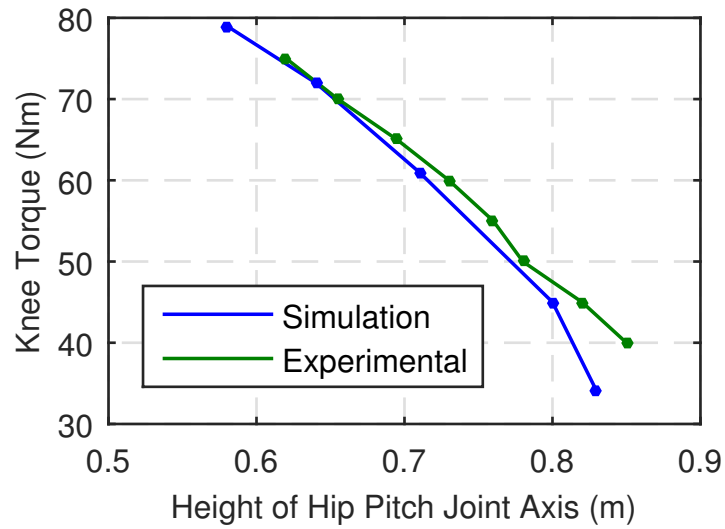


Figure 3.1: Comparison of knee torque required to maintain squatting pose of various heights between simulation and hardware testing[48].

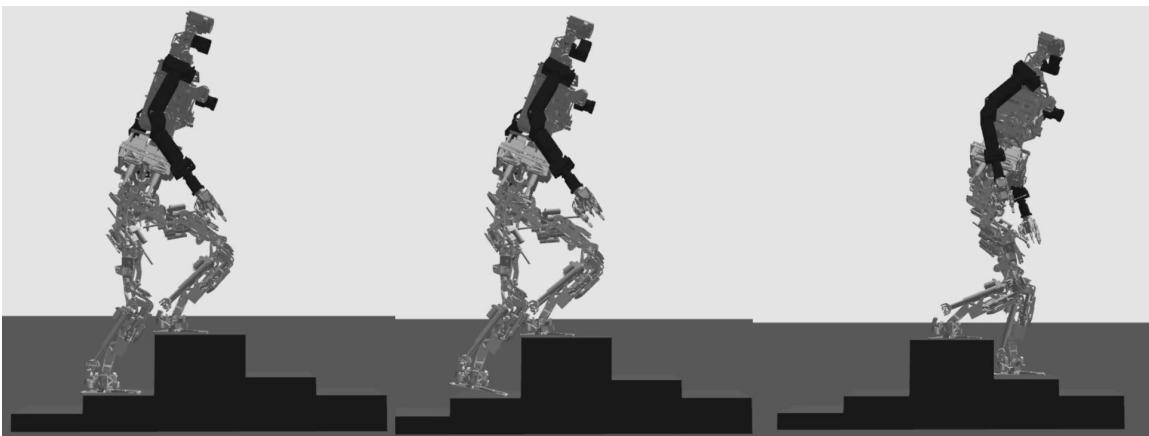


Figure 3.2: Sequence of steps simulated to generate predicted knee torques for ESCHER[48].

torque of 195 Nm at 110 deg. After analysis a dual actuator knee design was determined to be sufficient for an 80kg maximum robot mass.

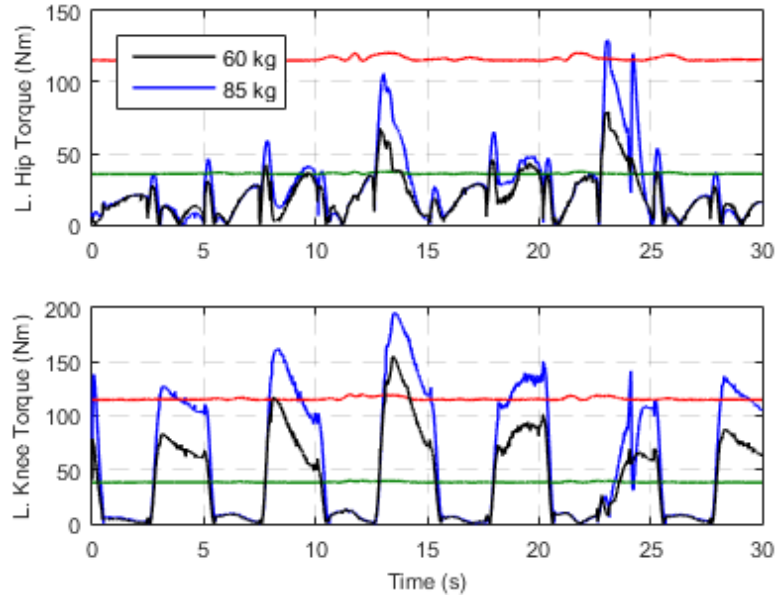


Figure 3.3: Simulated joint torques of a 60kg and 80 kg robot[48].

3.7 Mass Budget

Based on the simulation data a hard limit of 80 kg was given for ESCHER. A margin of 10% was allowed for cables and hardware growth for a total of 72 kgs. Development of a new leg design was given priority to ensure the ability to cross all the terrain that would be encountered during the DRC Finals. The increased knee torque would be provided by a dual actuator with a traditional lever arm providing a peak torque of 340 Nm, approximately a 3x increase from THOR's design. Sensors, computers and batteries determined by the various trade studies performed would need to be mounted as well as the new head design and arm design from THOR. Given these restrictions the total mass of the system was 68.75kg before the structure of the chest was even designed.

Chapter 4

Capabilities

4.1 Overall Design

The final design of ESCHER represented an almost complete redesign of THOR. Every major component except the shins had some redesign work performed on it. ESCHER maintained 6-DOF legs and had the option of either 7-DOF Dynamixel arms or Adroit arms by HDT. Table [thor_vs_escher] provides a comparison of the two systems. This chapter will describe the design decisions to meet the performance requirements of the DRC.

Table 4.1: Comparison of THOR and ESCHER

	THOR	ESCHER
Mass (kg)	61.3	77.5
Height (m)	1.78	1.78
Arm Span (m)	2.06	2.41
Processors	2x i7-4700E 1x i7-4770R	2x i7-4700E 2x i7-4770R
Battery Capacity (Wh)	N/A	710
Arm DOF	9	11
Total DOF	34	38

4.2 Mechanical Design

Initial mechanical design took place before the finalization of the electrical system or the decision to use the Adroit arms. Special attention was paid to flexibility in design. Features to allow expansion with minimal remanufacturing. Open spaces were left for airflow and

doors created to allow easy access to the interior for debugging and programming. Design began with the battery compartment. Batteries were situated as close to the center of mass as possible to minimize the torque required to move the chest. The selected batteries utilized were lithium polymer packs with a volume of 158mm x 59mm x 141mm. Due to the tendency of lithium batteries to puff or expand after use and to allow for padding extra spacing of 3mm per side were left in the battery compartments. Central support columns were added to allow for thinner walls and shelves by carrying the load through the center of the chest into the main cross roller bearing that supported the upper body.

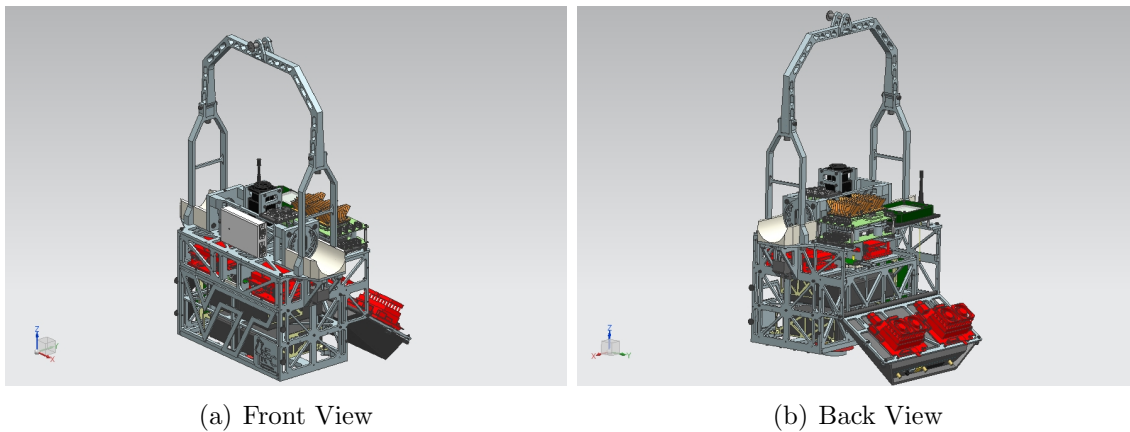


Figure 4.1: The computers for ESCHER highlighted in Red

Figure 4.1 shows the computers in the chest highlighted in red. As the heavier computers, the Brix's were placed above the main bearing on the shelf directly above the batteries. Cutouts were made in the interior support walls to prevent impeding the airflow from the computers cooling fans. The FTDI board to allow communication to the Dynamixel servos was placed in the space in between the computers using a lightweight 3D printed mount. The FTDI board was a source of frequent maintenance problems and required frequent replacement. The central location allowed for quick replacement and minimized the stress placed on the board during installation while protecting it in the central part of the chest. The PC-104 computers were mounted on a back panel that could swing open to provide access to all 4 computers and the internal wiring harnesses. The back panel was held on by 4 captive thumb screws to prevent bolts dropping into the interior of the robot and causing a short circuit. The door also provided an excellent mounting point for the router used for the wireless communications. The top plate provided the mounting points for the arms, head, power distribution system and emergency stop. Long cross members were placed to transfer the load of the arms down through the center of the chest. These cross members were specific to the arms used. In total swapping between the arms required 6 parts to be added or removed. An overhang was added to the top plate to provide a larger shoulder width. This allowed space to mount equipment on the side walls of the chest without compromising workspace. To help transfer the load into the sidewall these overhangs were supported by

gussets that transferred the load into the shelf carrying the computers. properly transferring this load with the Adroit Arms proved challenging as the servos that make up the arms are cylindrical and need to freely rotate. This placed the entire load of the arms on the cross members. Figure 4.2 shows the 3D printed bushing made out of Ultem 9085 thermoplastic to solve this problem. Ultem provided a smooth surface and high temperature resistance as well as the stiffness needed to prevent sagging. While the Ultem could be tapped, the holes needed to be printed with thicker areas of solid material to provide sufficient surface for threads. The adroit arms are mounted with a proprietary system, typically designed to be mounted to a mobile traded base such as a TALON or iRobot Packbot. Custom mounting plates were designed that required shipment to HDT for addition of the proprietary connector. These plates were incorporated into the existing design so that only 4 additional holes and 4 additional parts needed to be manufactured in order to change the arms configuration.

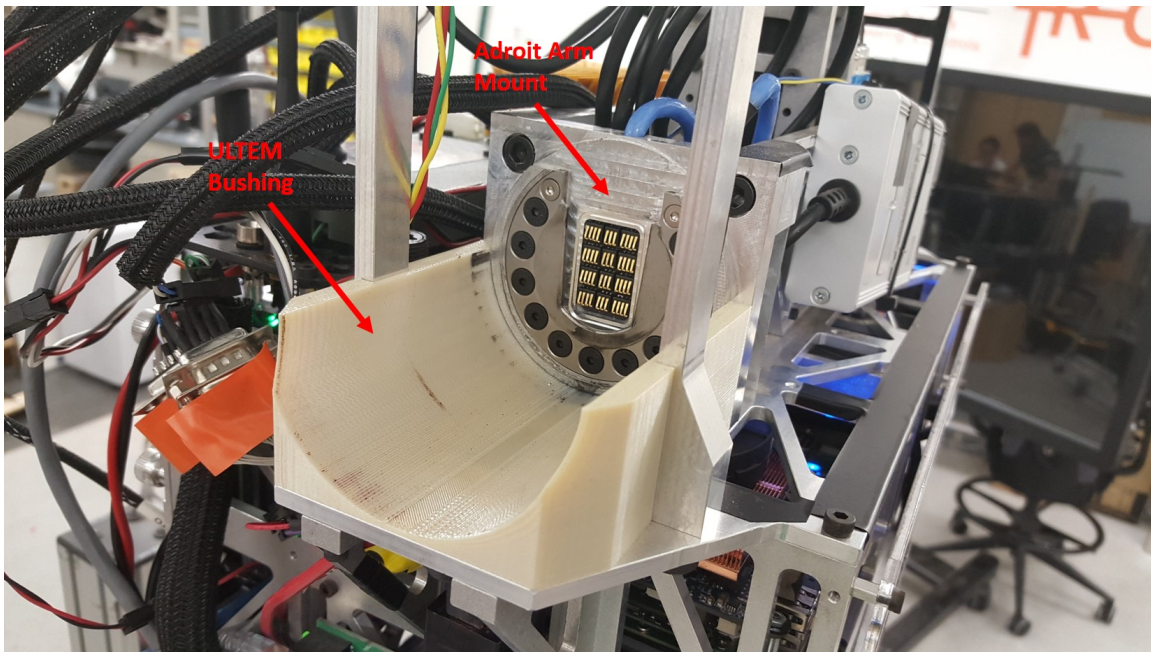


Figure 4.2: Ultem support bushing

The rear of the top plate was left open for the power distribution and emergency stop. Pre tapped holes were scattered on the top and sides of the chest to provide mounting points for hardware. Though these holes were unlikely to match any premade circuit boards or sensors, Delrin adapter plates could be easily designed and manufactured on a laser cutter. The power distribution system could be designed without concern for the preexisting mounting pattern, simplifying the design process.

4.3 Perception

The perception system maintained a similar interface from THOR. The servo for the neck was elevated above the top plate to keep the sensors in the same position on both robots. This allowed for development on THOR while ESCHER was under construction with minimal differences. The front cover of the computer shelf maintained the mounting holes for a second LIDAR in a pitch configuration for ground scanning however it was not utilized for the competition.

4.4 Electrical and Computer Systems

The electrical system was required to provide power to multiple buses from the battery packs. Each shelf of batteries was wired in series to provide a 48 V bus. The lower shelf was used to power the lower body of the robot with the upper shelf powering the upper body. The power distribution system provided power to 5, 12, 15 and 24V buses on the upper body. Batteries were divided into two buses with two battery packs wired in parallel for 24V power and two batteries wired serially for 48V bus power. The final Computer system was 2 Gigabyte Brix Pro computers with i7 4770R processors and two ADL PC-104 computers with i7 4700E processors. The Brix computers were modified by removing their outer case for weight and wireless cards to allow access to both miniPCI Express slots for CanBus connections a custom 3D printed mount for the hard drives and miniPCI-E cards was attached to the baseplate as shown in Figure 4.3. This modification allowed the half sized miniPCI-E port on the Brix to accommodate a full sized dual channel CanBus card. The PC-104's were in a standard configuration with a second Ethernet port to receive data from the Multisense camera and optional FLIR A35 infrared cameras. All computers were configured with 32 GB of Ram and 500 GB solid state hard drives.

Computers and sensors were networked through a 8 port 1 Gb switch. Motor control and the force torque sensors were commanded via CanBus. Multiple objects on a single CanBus can cause packet collisions which decreases bandwidth. To preserve bandwidth 6 separate buses were used three for the legs, two for the arms and a separate bus for the force torque sensors. The legs required the extra CanBus Channel due to the additional actuator in the knee which reduced the bandwidth to unacceptable levels. This number of buses posed a challenge since the Brix computers could at most mount 4 CanBus channels each through the mini-PCI Express slots. Eventually a 2 Channel USB to CanBus adapter was mounted on the front of the robot. The USB provided increased latency to the arms, but as the arms were weighted much less in the momentum controller this was deemed acceptable. The use of USB also prevents the implementation of a real time control system as USB is not deterministic. Several of the motor controllers have the same problem however, so any desire to implement real time control would require significant changes to the system.

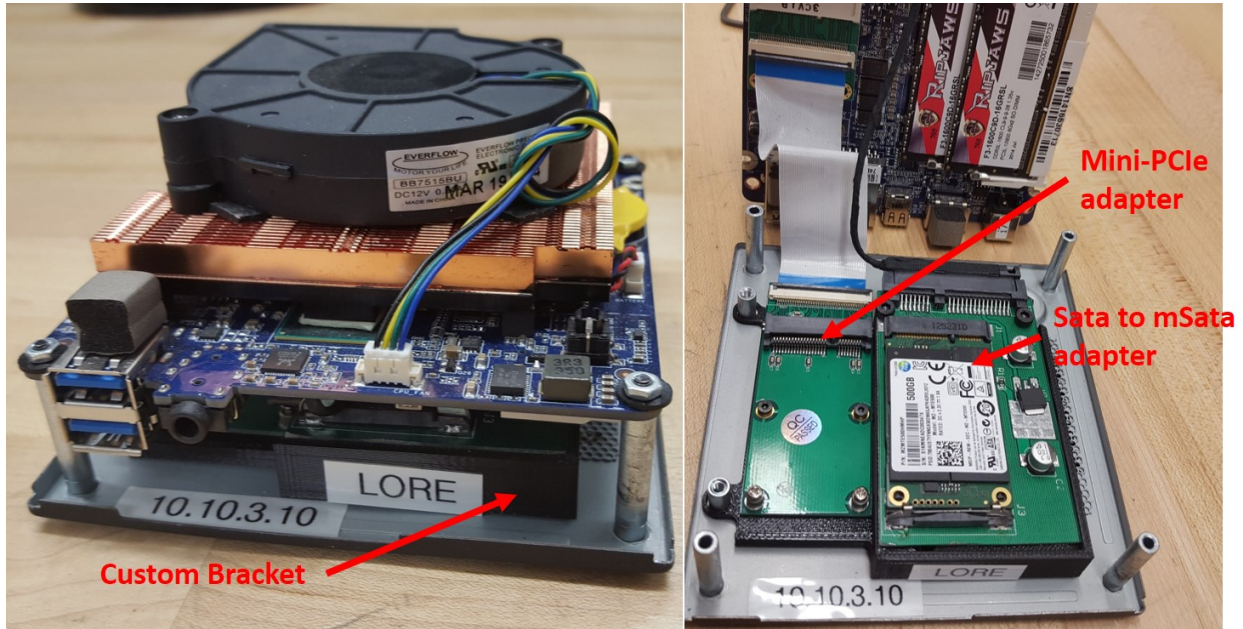


Figure 4.3: Custom mount for hard drive and miniPCI-E boards

4.5 Maintenance

Significant effort was placed in reducing maintenance times. The open structure of the chest allowed for both lighter weight and ease of access with tools. Wherever a bolt was used space was allocated for a tool to be inserted and manipulated. For example in order to allow better access to the bolts mounting the Brix computers cutouts were placed in the battery shelf to ensure a hex wrench would fit inside the battery compartment. Though still constrained by the battery compartment this allowed for much quicker removal of the computers if needed. Similarly bolts used were minimized wherever possible reducing the bolts holding on a motor from 28 to 16. Previously the removal of a shoulder motor was a multi-hour process requiring the removal of the battery housing and gantry mount forcing the robot to be placed on it's support pedestal. Additionally disconnecting data and power connections was difficult due to the small access cutout shown in Figure 4.4. Two data lines for the serial bus connecting the Dynamixel servos and a power line with a MOLEX mini Fit jr connector were required to fit into the space shown. By removing the plate covering the top of the motor connectors could be easily accessed and changed without removing the robot from the gantry. Overall bolt weight increased from 380g on THOR to 396g on ESCHER but access to bolts with standard tools was improved. All components could be accessed and removed independently reducing the risk of damaging additional components during maintenance, a common issue with THOR.

The rear door provided significant time savings for the software team. Though typical development was performed via remote terminal the ability to quickly connect a keyboard,

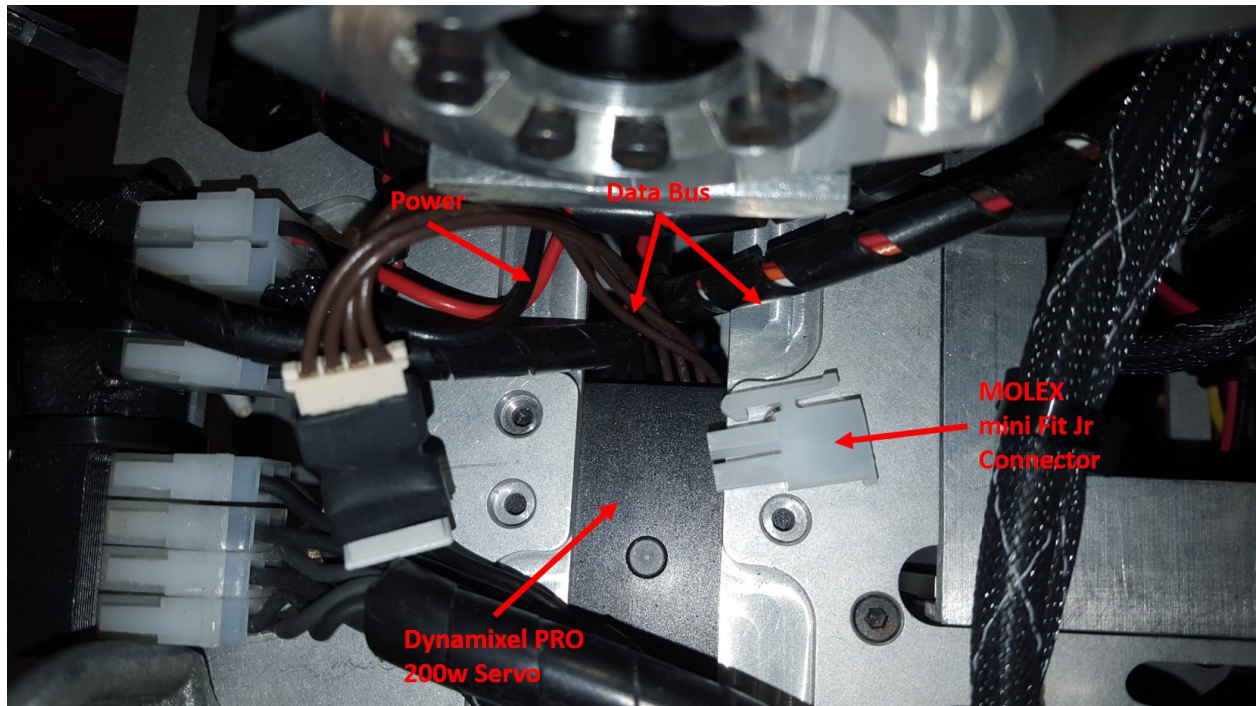


Figure 4.4: Access point for power and data connections for THOR shoulder servo

screen and mouse proved invaluable for debugging. The space between the PC-104's and Brixes provided an excellent path to run wiring harnesses, keeping them protected and allowing them to be lashed to the frame. Many issues arose on THOR due to connectors becoming faulty from movement. By having dedicated areas to lash the bundles to the frame extra movement and strain placed on the connectors was minimized.

Chapter 5

Results

5.1 Overall performance

The time taken to analyze the deficiencies in THOR and redo the requirements was necessary to ensure ESCHER could meet the performance goals of the DRC. By designing to a minimum requirement and leaving sufficient design margin ESCHER not only met but exceeded the performance requirements of the DRC. The compressed development time line of the DRC finals left 43 days for testing and debugging of the system. ESCHER was able to demonstrate the ability to achieve all of the DRC final tasks except exiting the vehicle and successfully walked the 61m at the DRC. Escher also survived a fall on day 1 with little damage. ESCHER's design carried more computing and had a longer battery life than its competitors as an all-electric system. Though not as strong as hydraulic robots, ESCHER proved more than capable of the DRC tasks and showed the potential of electrically actuated robots.

5.2 Mechanical requirements

Mechanically the chest needed to be lightweight, but stiff enough to prevent flexing and distortion of the perception system. The mass of batteries alone was 50% more than the chest of THOR and with the additional sensors and computers only 3.25 kgs were available before engineering margin was consumed. Due to the loss of in-house manufacturing capabilities parts needed to be kept simple in order to reduce cost of outside machining.

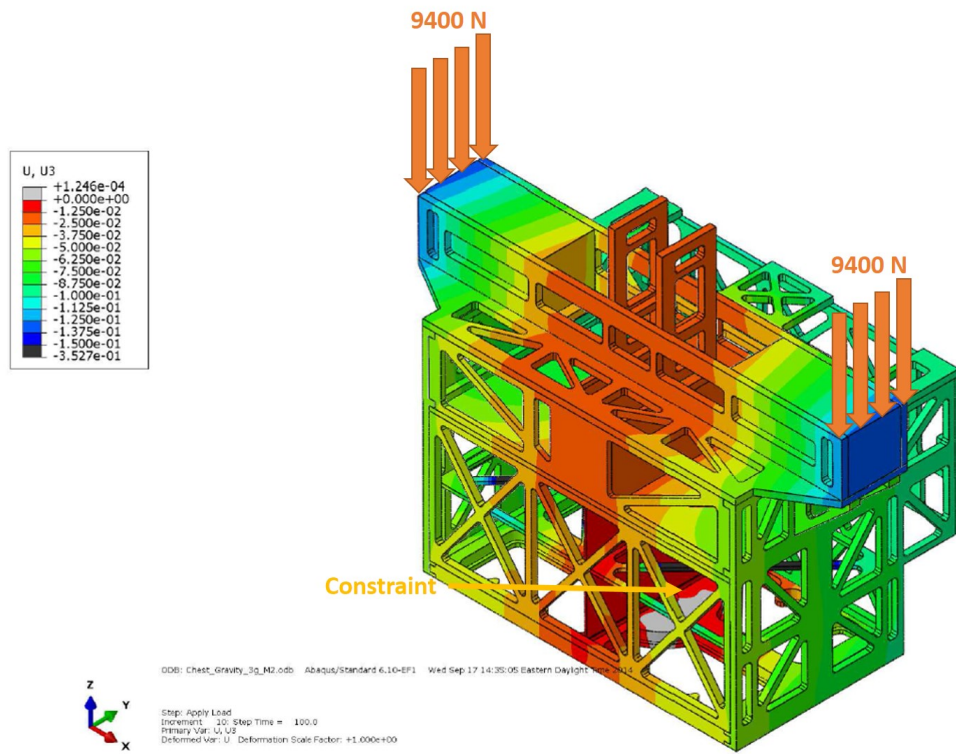
5.2.1 Mass Budget

In order to meet mass budget requirements the chest structure was redesigned to carry load down the center of the body into the main cross roller bearing. This allowed thinner walls than the THOR designed which maintained a hollow chest cavity for the battery pack. The most significant outside source of load would come from the arms holding an object while performing manipulation tasks. The Adroit Arms weighed 8.4 KG's producing a torque at the mounting point of 90 Nm at full extension plus whatever the carried payload contributed. Originally based on the potential sensor load 3.25 kgs were allocated for structural mass. Finite element analysis, shown in Figure 5.1 reduced mass from an original mass of 5.753 kg to 4.693 kgs. Though this exceeded the budgeted mass, base sensor and battery mass was reduced as the design matured. Additional hardware and sensors were able to be mounted while still keeping the overall mass of the robot down below the 80 kg maximum.

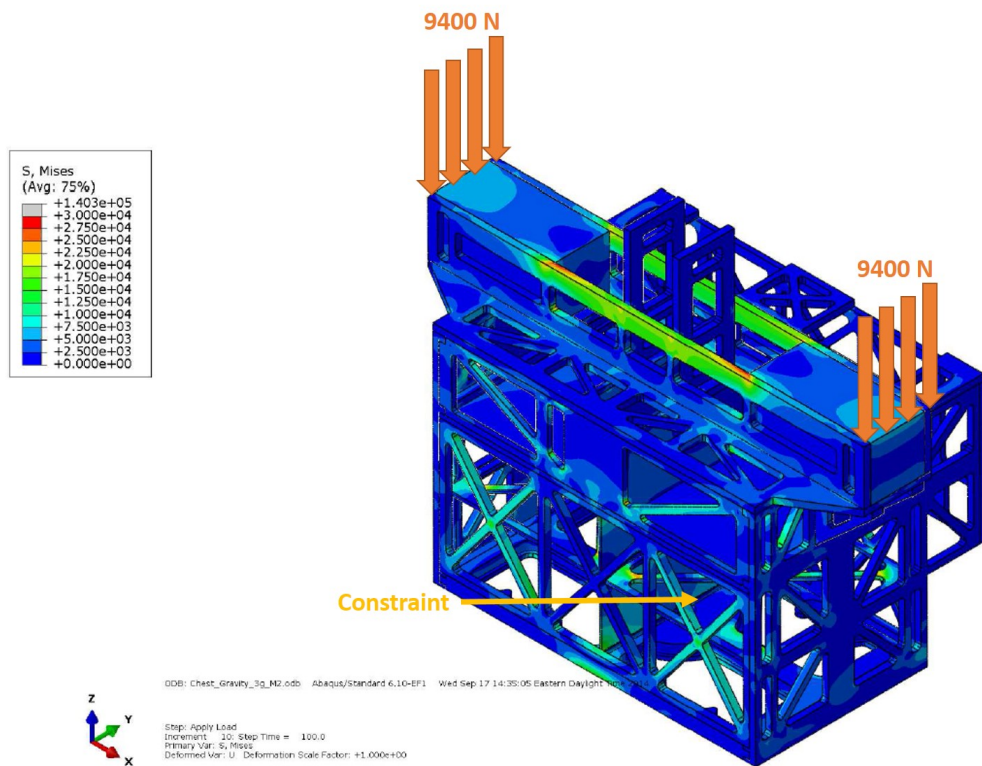
The most significant mass reduction occurred after the DRC testbed event held from March 3rd to March 13th of 2015 in Charleston South Carolina. While the lower body of ESCHER was still under assembly the upper body was mounted on a wheeled platform, known as Rene, to develop the Perception and manipulation systems. During the field testing with Rene, All systems were in close to final configuration, having mounted the missing power distribution boards, Wireless communications and emergency stop buttons. Smaller test batteries were used to power Rene, carrying 3 22.2v 8,000 mAh batteries. Rene showed significantly better energy efficiency than expected, operating for 4 hours on a single battery charge. Walking efficiency of ESCHER was not expected to vary significantly from THOR, and a final decision was made to use 4 of the smaller batteries during the competition to save 6.4 kgs. Even with this reduced battery load the final ESCHER design showed a battery life of up to 2.5 hours on a single charge. Additional mass savings from initial estimates was achieved by removing cases from computers and network switches as well as removing a network switch entirely. In the case of the network switches mass was reduced from 0.528 kg to 0.192 kg. With the removal of the second switch 0.864 kg total were saved. Removing the cases from the Brix computers reduced the mass from 0.897 kg to 0.692 kg for a total of 0.49 kg of mass savings. The total savings of 1.354kgs brought the allowable structural weight up to 4.6kgs. With the final design weight after finite element analysis of 4.665 kg the chest design was considered a success in terms of mass weighing 11% less than the 5.173 kg of the THOR chest.

Finite element Analysis

Finite element Analysis was performed on the initial design of the chest for both structural stiffness and to reduce mass. Abaqus was utilized for meshing and analysis. The experiment neglected bolts and assumed a 3 g load in the -Z axis. Component masses were modeled as closely as possible with the Arms modeled at full extension with the shoulder joint rolled 90. As shown in 5.1(a) Maximum displacement was at the shoulder joints showing a maximum of



(a) Displacement due to 3G load



(b) Stress due to 3G load

Figure 5.1: Finite element analysis of original ESCHER upper body

0.1375 mm, roughly on par with tolerance errors in standard machined parts. The increase in mass of the Adroit Arms to 8.3 kg per arm from the modeled 6 kgs would be the equivalent to a 1.4 g load, still providing over 150% factor of safety. The stress analysis shown in 5.1(b) showed highest concentrations at the intersection of the shoulder motors and support housings. This however was an artifact of the modeling technique seeing this as a 90 angle. Even at the maximum of 2.75 kPa the stress is well below the yield strength of 241 MPa for the 6061-T6 aluminum used to manufacture the chest. Based on the data from the finite element analysis wall thickness was decreased x mm while the thickness of the I-beams through the central battery chamber was increased to solid 4mm. This had the added benefit of reducing the parts complexity to manufacture. Additionally the gussets under the arm were thickened and extended to move the load directly into the support plate for the Brix Computers. With these modifications 1.159 kg's were removed from the overall structural mass.

5.2.2 Volume

One of the original requirements was to maintain the same volume for the chest on ESCHER as was used on THOR. The goal was to preserve workspace in front of the robot for manipulation. Shoulder width was also a concern to allow the robot to walk through a door without colliding with the door frame. A bounding box of 305 mm x 347 mm x 200 mm was originally requested with a shoulder width of 535mm. Due to the width of the original battery packs the target of 305mm in width for the chest proved impossible. Due to Lithium polymer batteries having a tendency to expand and to provide some room for foam padding 3mm of space was left on each side of the battery cavities. With 4.76 mm wall thickness the total width of the new chest expanded to 318 mm. This further increased with the relocation of the network switches from the bottom of the chest to the sides. The shoulder width also expanded with the change to the adroit arms to a total of 663 mm. While the increase in width was significant it proved to be irrelevant. The sway during locomotion proved too risky for even THOR to walk through a doorway. Walking through the door was instead achieved through sidestepping. Additionally the optimal workspace for manipulation proved to be directly to the side of the robot not in front. As a result all manipulation occurred with the robot turned sideways towards its target. Overall the new volume of the chest was 318mm x 341 mm x 229mm. Though slightly deeper this was still within the volume defined by the IMU the furthest point back on the robot.

5.2.3 Arms

In December of 2015 HDT Global became a sponsor of team VALOR and agreed to provide their 7-DOF Adroit Arms for the DRC. These arms represented a significant upgrade to the Dynamixel Pro arms that had been used on THOR but posed unique design challenges.

Since their use would only be a loan the chest had to be able to transition between mounts for the Adroit arms and the Dynamixel without significant changes to the system. The largest accommodation for the Adroit arms was the increased mass. The Dynamixel configuration had a mass of 10.4 kgs and flat mounting surfaces, allowing the load to be easily transferred from the motor housing to the top plate and sides of the chest using gussets. The Adroit motors are cylindrical and the enclosure itself rotates. This meant that the entire load was carried at the mounting plate. With a lifting capacity of 27.3 Kg's per arm a support solution would be needed to effectively transmit the load into the frame. Additive manufacturing materials were analyzed to great a lightweight bushing that would support the loads the required. While ABS was considered as a material ULTEM was eventually selected due to its heat resistant properties and high quality surface finish. A full swap from Dynamixel to HDT arms can be performed in less than 2 hours.

5.2.4 Manufacturability

During the transition to a new lab space significant manufacturing capability was temporarily loss. The 3 axis Bridgeport mill used to manufacture a significant portion of THOR was completely unavailable. Combined with reduced funding due to the teams placement in the trials keeping cost down to a minimum was a key requirement. When a part needs to be rotated in the mill it can take up to 30 minutes of a machinists time. At anywhere between \$80-\$150 per hour for a manufacturing refixturing operations can add significant cost to a part. With 22 Parts in the chest keeping manufacturing simple would keep costs down. Only the bottom plate required a second operation to cut the tabs for mounting into the sides of chest. Primary cost drivers were larger plates with the top mounting plate being the most expensive. However, the entire chest was manufactures for \$3,500 with only a two week turnaround time.

5.3 Perception requirements

In order for 6D SLAM to be possible the precise locations of the sensors is critical. Based on the finite element analysis the neck mount will deflect 0.01 mm well within the accuracy of the most common SLAM techniques [citation] Mounting points were incorporated to still allow the use of a chest LIDAR though it would require the addition of a second switch to allow for sufficient connections to the onboard network. Due to the workspace of the arms the head cage obscures a portion of the available workspace, but there is sufficient coverage to allow for the opening of doors and turning of valves. Onboard networking allowed for up to two 8 port gigabit network switches. These switches allowed communication between the onboard computers and the perception sensors. When configured for the DRC only 1 network switch is necessary since the FLIR A35 cameras and Chest LIDAR's are not utilized.

5.4 Electrical Requirements

Accommodating the electrical system presented several challenges. Battery mass was the second largest component carried in the chest after the arms. Accommodating the batteries drove the volume of the chest. Second, the power distribution boards had not been designed at the time of manufacture. Third, space to accommodate wiring and network cabling had to be allocated. The main battery area is designed to accommodate the 4 22,000 mAh batteries providing 2200 Wh of energy plus padding and to allow for slight expansion due to battery use. With the decision to use the smaller batteries 4 abs brackets were designed to mount to pre-existing holes in the frame. These brackets helped prevent sliding of the smaller batteries during locomotion. Additive manufacturing was used to keep the parts light and simple to manufacture though foam was needed to reinforce the empty space in the chest cavity. Large flat spaces were left open as potential mounting points for the power distribution system. To ensure any circuit board design could be mounted a variety of tapped m3 holes were spread across the top and sides of the chest. Laser cut delrin plates could be quickly cut to match the hole pattern on the chest as well as allowing the addition of standoffs to support the circuit boards. Impact protection would be provided by a second sheet of delrin on top of the circuit boards. Power distribution and emergency stop boards were placed in the large flat open area behind the neck. This area was protected from fall and impact damage and allowed easy access for maintenance and debugging. While a large power cable came off the left side of the robot, by locating the boards behind the arms there was no interference during manipulation. Large open spaces were left in the computer cavity to allow for wiring for power and networking. Cables were run across the back of the chest between the body cavity and back plate on which the PC-104's and wireless communication switch were mounted. This space was left open in order to allow adequate airflow and to prevent requiring connectors to bend too sharply.

5.5 Maintenance Requirements

One of largest issues with THOR was the time required for maintenance. Though not a hard requirement simplifying maintenance tasks was greatly desired. Special attention was paid to minimizing the amount of bolts necessary to mount components and to ensure plenty of space was allowed for connectors and tools to access the bolts. The door on the back of the chest swung open to allow access to the computers and plug in external monitors and keyboards for debugging. Changing a Dynamixel shoulder motor was reduced from a 3 hour process to 45 minutes. Another source of frequent maintenance, the FTDI board was moved internal to the chest between the Brix computers. Previously replacement on THOR required either bending the FTDI board past the carbon fiber tubes or disassembly of a significant portion of the chest. On ESCHER the FTDI board requires simply required opening the back cover and removing two bolts. By preventing the need to bend the board

it is likely that the life of the FTDI boards was significantly extended. On THOR an FTDI board was replaced approximately every two months, since moving to the ESCHER platform an FTDI board has yet to be replaced.

5.6 DRC Performance

The DRC provided three opportunities for ESCHER to attempt the course. The first day was a practice run and Day 1 and Day 2 were the official runs for the competition. The decision was made to use a safety gantry on the practice run automatically placing the team last in the standings. ESCHER successfully walked the 61m driving course on the second day of the DRC, one of only two robots to successfully do so.

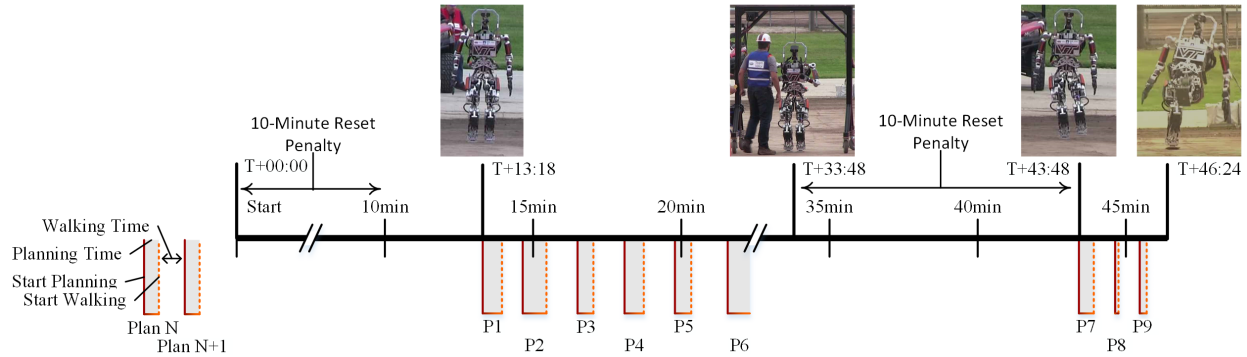


Figure 5.2: Timeline for day 1 of the DRC[50]

Though there were initial concerns that the dust and sand of the course could damage the exposed electronics, there was no noticeable effect on functionality. Figure 5.2 shows the time line of the first day of competition. Due to configuration issues with the new course for the Day 1 attempt several of the robot's systems failed to initialize. In its degraded capacity ESCHER was still able to walk to the first third of the course until a known bug was accidentally triggered where the robot was asked to plan too many footsteps. Unable to recover the robot was rest and the course attempted again. At this point an error in the left hip pitch motor controller caused the transmission of a constant velocity resulting in a fall. The first point of impact was on the IMU where foam fall protection covers had been added. The second point of impact was the left arm followed by the wireless router mounted on the back of the chest. Analysis of the video shows the chest supporting the entire weight of the robot during the fall.

Though some damage occurred to the knee actuators minimal repairs were needed to bring the robot back to operational capacity. Though covered with dust and dirt compressed air was simply used to blow the components clean and operational capability was restored. Though the IMU mount which took the first impact suffered some deformation, no significant

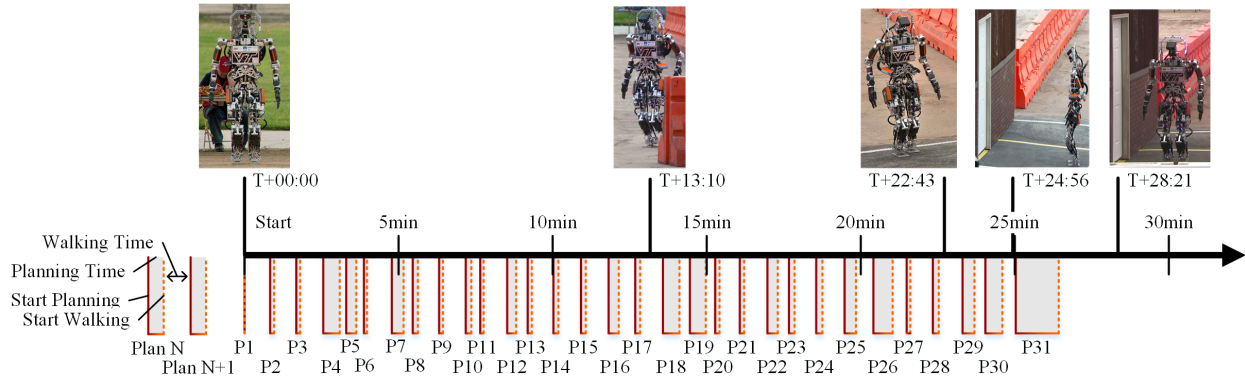


Figure 5.3: Timeline for day 2 of the DRC[50]

structural damage occurred to the system. The robot was ready for its run on Day 2 as shown in Figure 5.3 and successfully walked the 61m course in 22:43m. Unfortunately due to an issue with a wrist encoder the robot was unable to open the door and score a point. With the successful completion of the walking course ESCHER became the first humanoid to walk the entire course untethered and only one of two to successfully do so at the DRC.

Chapter 6

Future Work

6.1 Design Analysis

Through proper design and analysis the design of ESCHER not only met the requirement imposed by the DRC but far exceeded them. ESCHER had more processing power and longer battery life than any competitor at the DRC with similar capabilities. Post DRC testing showed the ESCHER completing all of the DRC Tasks except for the driving task. Beyond the DRC ESCHER will be used in the Shipboard Autonomous Fire Fighting Robot (SAFFiR) project for the US Navy. Fire fighting situations pose challenges even the DRC did not account for such as high temperatures, water and obscuring smoke. Improvements in all these areas will be necessary to make ESCHER a viable platform in emergency situations.

6.2 Knowledge Transfer

ESCHER's design was successful due to the experience of the team and accumulated knowledge base. Complex competitions like the DRC are rare for academic institutions requiring a change in approach from normal academic research. The design of ESCHER was successful due to the incorporation of techniques from industry and adjusting them to the smaller team. Proper selection of tools and process greatly accelerated the development timeline of ESCHER. Though ESCHER has sufficient capability for years of research ensuring adequate knowledge transfer to incoming researchers will be vital for continuing development. For example maintaining the CAD repository with the most up to date versions of THOR and ESCHER is vital for the motion system to accurately control and balance the robot. The final weight of ESCHER on a hanging crane scale is 77.5 kg while the CAD model lists its weight as 74.7 kgs, an error of less than 5%. By keeping this error low simulation can accurately be used to predict performance due to upgrades and changes. The CAD repository

is also used to track the history of the various configurations of the robot and can allow for relatively quick changes, such as changing the HDT Adroit Arms back to the Dynamixel Arms. With the end of the DRC funding will be reduced and students will graduate. A precision machine like ESCHER requires constant maintenance and monitoring. Ensuring knowledge is transferred to new members of the team while still performing cutting-edge research will be a difficult balance that must be actively monitored.

6.3 Covers

The need for a lightweight upper body drove the design to maximize the use of lightening holes. While useful for access to the interior of robot, a dust or smoke filled environment would offer little protection. In addition ESCHER will be used as the platform for the follow-on to the Shipboard Autonomous Fire Fighting Robot (SAFFiR) project. Fire hoses can have significant back spray and the water will immediately flash to steam when it hits a flame. Proper environmental covers will be required to realistically operate in a firefighting environment. Additionally covers will need to provide better impact protection in case of falls. The polystyrene covers used on ESCHER successfully protected against the fall on day 1 of the competition, but were significantly compromised after the fall. It is unlikely they would protect from a second fall. The polystyrene covered certain vital areas, but protection of other areas of the robot are required. Covers must be lightweight, water proof and not limit mobility. The effects of covering the computers must be analyzed for its effect on their operating temperature. Stress testing has shown that current draw is the primary limiting factor at the moment, but once enclose by a water proof cover the temperature may be a larger issue. The frame of the robot has proven to be a reliable heat sink, but may not be sufficient for sustained operations in high temperatures. Access to the interior of the robot will provide a challenge. One of the large advantages of the system as designed is the ease of maintenance and access to the computers and micro-controllers. Any system of covers should attempt to minimize the additional steps necessary for maintenance. Covering diagnostic lights and preventing access with measurement tools will make it very difficult to perform diagnostics. The ability to rapidly diagnose and detect errors in the field greatly improves the utility and efficiency of testing.

6.4 Temperature Protection

Regardless of the properties of the covers, temperature protection will be necessary for the electronic components of the robot. Fires in enclosed areas can melt steel, and even approaching a high temperature heat source can quickly overwhelm not only the computers, but the drive motors as well. An active cooling system will be vital to operations in firefighting scenarios. The frame of the robot provides 26 kgs of aluminum for thermal

dissipation. Use of heat pipes may allow sufficient heat transfer to the frame to allow for higher temperature operations. Proper design of the covers would also allow for airflow along the inside of the robot. Airflow channels were intentionally cut for the current heat sinks on the Brix computers, but the open structure of the chest should allow for easy airflow.

6.5 Falls and Fall Recovery

While ESCHER survived a fall during the DRC it was unable to pick itself up afterwards. In a real world disaster, surviving a fall is of little use if the robot can not pick itself up and return to an area an operator can repair and evaluate it. ESCHER was design with the ability to stand up in mind but it is unclear if it will be capable. The knee brackets in the front were designed to allow ESCHER to rest in a kneeling position when standing from laying on its front. it is unclear if a dynamic motion will be required to return to its feet however. Similarly the arms have the required range of motion when laying on it's back to stand itself up, but may lack the velocity in the actuators to stand. Tied to standing is designing the covers and fall strategies to ensure the robot falls into a position which can be recovered from. A method is also needed to ensure that the robot falls into a known position as well that minimizes damage. Research is beginning into using techniques derived from martial arts such as Judo and Aikido to minimize falling damage, but none of this research has been applied to a full sized humanoid. Proper falling will be critical especially with non back-drivable servos such as in the Adroit arms. A fall on these motors could cause significant damage, but the ability to use torque control to simulate various spring constants in the joint may provide the ability to fall safely and in a controlled manner.

6.6 Knowledge base

A custom platform like ESCHER provides significant advantages to a research group. By designing and developing the hardware in house designs can be rapidly tested and improved upon. The disadvantage is that many of the lessons learned through design iteration often remain with the designer or manufacturer. This is especially difficult in an academic setting where students will transition through the project regularly. An advanced system like ESCHER will need continual maintenance and passing the knowledge on to new members of the project will be critical to keeping the robot as a viable research platform. The difficulty in maintaining a teams knowledge base is maintaining information in proper locations while preventing the creation of so many databases the information is lost. For example data for the maintenance of ESCHER is stored in a team wiki, the Software team wiki, the software bug tracker, the issues list for the mechanical team, and the database for AGILE tasks[citation]. Each of these databases contains information related to the continued operation of the robot that can be easy to lose track of. In addition some information may be duplicated among

multiple of the databases. Simply keeping the systems operating involves a significant amount of time and specialized knowledge. Without dedicated effort the databases can quickly become out of date and obsolete. In an academic setting infrastructure maintenance can easily be disregarded by students and faculty. Maintaining databases and knowledge systems does not directly help with research and experimentation, lowering the incentives to dedicate time and effort towards these tools. However, poor exchange of information can lead to damage and repeated effort. For example failure to properly calibrate the load cells can result in unexpected movement. At full speed ESCHER can easily react faster than the emergency stop can be activated putting both workers and hardware at risk of damage. A damaged part can keep the robot off-line for a month or more, making prevention a worthwhile area to invest in.

6.7 Data Capture

While data logs were captured for much of the testing from the ROS components of the software system little data outside this exists for much of the testing. ROS includes built in data logging but many of the custom subsystems are unable to provide any sort of logging data. For example there is no method to log data on the CanBus leading to significant guessing to diagnose problems with the low level motor controllers. The team has assumptions as to what caused the error on Day 1 of the DRC leading to the fall, but no solid data. Often issues with the MotorSlugs simply resulted in changing out the offending controller with no understanding of what caused the issue. Similarly the motion system evaluations could be made during simulation as to how fast the control loop was running, but there was no method to determine on-board performance. No knowledge exists for which situations cause errors or drops in performance on the motion system. Use of 3rd party software to monitor computational resources was attempted, however the current software system is incompatible with the tools as written. Planning for data logging early can greatly aid design and development as well as maintenance. Instead of depending on trained experts who are able to diagnose problems through experience, a wider variety of team members could diagnose problems and make the desired repairs.

Bibliography

- [1] Michael A. Hopkins. “Dynamic Locomotion and Whole-Body Control for Compliant Humanoids”. PhD thesis. Blacksburg, VA: Virginia Polytechnic Institute and State University, 2014.
- [2] B. Lee. “Design of a Humanoid Robot for Disaster Response”. MA thesis. Blacksburg, Virginia: Virginia Polytechnic Institute and State University, Dec. 2014.
- [3] A. Meier. *The Sensational Return of a Smoking, Walking, Talking World’s Fair Robot*. 2013. URL: <http://www.atlasobscura.com/articles/elektro-the-robot> (visited on 03/21/2013).
- [4] M. Vukobratovic, A.A.Frank, and D. Juricic. “On the stability of biped locomotion”. In: *Transactions on Bio-Medical Engineering* 17.1 (1970), pp. 25–36.
- [5] H. Lim and A. Takanishi. “Biped walking robots created at Waseda University: WL and WAIBAN family”. In: *Philosophical Transactions of the Royal Society* 365.1850 (2007), pp. 49–64.
- [6] K. Hirai et al. “The Development of Honda Humanoid Robot”. In: *IEEE International Conference on Robotics and Automation*. Leuven, Belgium, May 1998, pp. 1321–1326.
- [7] *Casualty Costs of Fuel and Water Resupply Convoys in Afghanistan and Iraq*. 2010. URL: <http://www.army-technology.com/features/feature77200/feature77200-3.html> (visited on 02/26/2010).
- [8] *Coalition Military Fatalities by Year*. 2016. URL: <http://icasualties.org/Iraq/Index.aspx>.
- [9] National Research Council (U.S.) Committee on Army Unmanned Ground Vehicle Technology. *Technology development for Army unmanned ground vehicles*. Washington DC: National Academies Press, 2002.
- [10] M. Buehler, K. Iagnemma, and S. Singh. “Introduction”. In: *The 2005 DARPA Grand Challenge: The Great Robot Race*. Ed. by M. Buehler, K. Iagnemma, and S. Singh. Berlin Heidelberg: Springer-Verlag, 2007, pp. XI–XIV.

- [11] P. Trepagnier et al. “KAT-5: Robust Systems for Autonomous Vehicle Navigation in Challenging and Unknown Terrain”. In: *The 2005 DARPA Grand Challenge: The Great Robot Race*. Ed. by M. Buehler, K. Iagnemma, and S. Singh. Berlin Heidelberg: Springer-Verlag, 2007, pp. 103–128.
- [12] C. Mutto, P. Zanuttigh, and G. Cortelazzo. “Microsoft Kinect Range Camera”. In: *Time-of-Flight Cameras and Microsoft Kinect*. Ed. by C. Mutto, P. Zanuttigh, and G. Cortelazzo. New York, NY: Springer US, 2012, pp. 33–47.
- [13] K. Kaneko et al. “Design of prototype humanoid robotics platform for HRP”. In: *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*. Vol. 3. 2002, 2431–2436 vol.3. DOI: 10.1109/IRDS.2002.1041632.
- [14] Kim Jung-Hoon and Oh Jun-Ho. “Realization of dynamic walking for the humanoid robot platform KHR-1.” In: *Advanced Robotics* 18.7 (2004), pp. 749–768. ISSN: 01691864. URL: <http://login.ezproxy.lib.vt.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=14222378&scope=site>.
- [15] M.Hirose and K Ogawa. “Honda Humanoids Robot Development”. In: *Philisophical Transactions of the Royal Society* 365.1850 (2007), pp. 11–19.
- [16] Yu Ogura et al. “Development of a new humanoid robot WABIAN-2”. In: *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006*. May 2006, pp. 76–81. DOI: 10.1109/ROBOT.2006.1641164.
- [17] T. Bushmann, S. Lohmeier, and H. Ulbrich. “Humanoid robot Lola: Design and walking control”. In: *Journal of Physiology-Paris* 103.3-5 (2009), pp. 141–148.
- [18] S. Kuindersma et al. “Optimization-based locomotion planning, estimation, and control design for the atlas humanoid robot”. In: *Autonomous Robots* 406.3 (2016), pp. 429–455.
- [19] Matt Zucker et al. “A General-purpose System for Teleoperation of the DRC-HUBO Humanoid Robot”. In: *Journal of Field Robotics* 32.3 (2015), pp. 336–351. ISSN: 1556-4967. DOI: 10.1002/rob.21570. URL: <http://dx.doi.org/10.1002/rob.21570>.
- [20] *Hybrid III 50th Percentile Male*. 2016. URL: [http://www.nhtsa.gov/Research/Vehicle+Research+&+Testing+\(VRTC\)/Hybrid+III+50th+Percentile+Male](http://www.nhtsa.gov/Research/Vehicle+Research+&+Testing+(VRTC)/Hybrid+III+50th+Percentile+Male).
- [21] I. Park et al. “Mechanical Design of the Humanoid Robot Platform HUBO”. In: *Journal of Advanced Robotics* 21.11 (2007), pp. 1305–1322.
- [22] G. Pratt and M. Williamson. “Series Elastic Actuators”. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Pittsburg, PA, Aug. 1995, pp. 399–406.
- [23] C. Knabe. “Design of Linear Series Elastic Actuators for a Humanoid Robot”. MA thesis. Blacksburg, Virginia: Virginia Polytechnic Institute and State University, Dec. 2014.

- [24] J. Pratt and G. Pratt. “Intuitive Control of a Planar Bipedal Walking Robot”. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Leuven, Belgium, May 1998, pp. 2014–2021.
- [25] T. Bushmann et al. “Dynamics Simulation for a Biped Robot: Modeling and Experimental Verification”. In: *IEEE International Conference on Robotics and Automation (ICRA)*. Orlando, Florida, May 2006, pp. 2673–2678.
- [26] A. Zoss, H. Kazerooni, and A. Chu. “Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)”. In: *IEEE/ASME Transactions on Mechatronics* 11.2 (2006), pp. 128–138.
- [27] *HAL for Living Support (Lower Limb Type)*. 2016. URL: http://www.cyberdyne.jp/english/products/LowerLimb_nonmedical.html.
- [28] *About the Company*. 2016. URL: <http://eksobionics.com/about/>.
- [29] *HULC*. 2012. URL: <http://www.lockheedmartin.com/content/dam/lockheed/data/mfc/pc/hulc/mfc-hulc-pc-01.pdf>.
- [30] M. W. M. G. Dissanayake et al. “A solution to the simultaneous localization and map building (SLAM) problem”. In: *IEEE Transactions on Robotics and Automation* 17.3 (June 2001), pp. 229–241. ISSN: 1042-296X. DOI: 10.1109/70.938381.
- [31] Nicolaus A. Radford et al. “Valkyrie: NASA’s First Bipedal Humanoid Robot”. In: *Journal of Field Robotics* 32.3 (2015), pp. 397–419. ISSN: 1556-4967. DOI: 10.1002/rob.21560. URL: <http://dx.doi.org/10.1002/rob.21560>.
- [32] *Hardware Specs*. 2015. URL: <http://www.willowgarage.com/pages/pr2/specs>.
- [33] *VLP-16*. 2016. URL: <http://velodynelidar.com/vlp-16.html>.
- [34] H. Kazerooni. In: *Experimental Robotics IX*. Ed. by M. Ang and O. Khatib. Berlin Heidelberg: Springer-Verlag Berlin Heidelberg, 2006, pp. 291–301.
- [35] Chen-Xi Zu and Hong Li. “Thermodynamic analysis on energy densities of batteries”. In: *Energy Environ. Sci.* 4 (8 2011), pp. 2614–2624. DOI: 10.1039/C0EE00777C. URL: <http://dx.doi.org/10.1039/C0EE00777C>.
- [36] H. Inoue et al. “HRP: Humanoid Robotics Project of METI”. In: *IEEE International Conference on Humanoid Robots (Humanoids)*. Boston, MA, 2000.
- [37] K. Yokoi et al. “Experimental Study of Humanoid Robot HRP-1S”. In: *International Journal of Robotics Research* 23.4-5 (2004), pp. 351–362.
- [38] C. Knabe, B. Lee, and D. Hong. “An Inverted Straight Line Mechanism for Augmenting Joint Range of Motion in a Humanoid Robot”. In: *ASME International Design Engineering Technical Conferences (IDETC)*. Buffalo, New York, Aug. 2014, pp. 1–6.
- [39] Viktor L. Orekhov. “Series Elasticity in Linearly Actuated Humanoids”. PhD thesis. Blacksburg, VA: Virginia Polytechnic Institute and State University, 2015.

- [40] M. Rouleau and D. Hong. “Design of an Underactuated Robotic End-Effector with a Focus on Power Tool Manipulation”. In: *ASME International Design Engineering Technical Conferences (IDETC)*. Buffalo, NY, Aug. 2014, pp. 1–7.
- [41] N. Koenig and A. Howard. “Design and use paradigms for Gazebo, an open-source multi-robot simulator”. In: *Intelligent Robots and Systems (IROS 2004), IEEE/RSJ International Conference on*. Vol. 3. Sept. 2004, pp. 2149–2154. DOI: 10.1109/IROS.2004.1389727.
- [42] V. Orekhov et al. “(An Unlumped Model for Linear Series Elastic Actuators with Ball Screw Drives”. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Hamburg, Germany, Sept. 2015.
- [43] A. Dietrich, T. Wimbock, and A. Albu-Schaffer. “Dynamic Whole-Body Mobile Manipulation with a Torque Controlled Humanoid Robot via Impedance Control Laws”. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. San Francisco, CA, Sept. 2011, pp. 3199–3206.
- [44] J. Kim et al. “Balancing Control of a Biped Robot”. In: *IEEE International Conference on Systems, Man and Cybernetics (SMC)*. Seoul, Korea, Oct. 2012, pp. 2756–2761.
- [45] L. Sentis, J. Petersen, and R. Philippsen. “Implementation and Stability Analysis of Polarized Whole-Body Compliant Controllers on a Wheeled Humanoid Robot in Uneven Terrains”. In: *Autonomous Robots* 35.4 (2013), pp. 301–319.
- [46] M. Hutter et al. “Toward Combining Speed, Efficiency, Versatility, and Robustness in an Autonomous Quadruped”. In: *IEEE Transactions on Robotics* 30.6 (2014), pp. 1427–1440.
- [47] N. Paine et al. “Actuator Control for the NASA-JSC Valkyrie Humanoid Robot: A Decoupled Dynamics Approach for Torque Control of Series Elastic Robots”. In: *Journal of Field Robotics* 32.3 (2015), pp. 378–396.
- [48] C. Knabe et al. “Design of a series elastic humanoid for the DARPA Robotics Challenge”. In: *IEEE International Conference on Humanoid Robots (Humanoids)*. Seoul, Korea, Mar. 2015, pp. 738–743.
- [49] M. Hopkins, D. Hong, and A. Leonessa. “Compliant Locomotion Using Whole-Body Control and Divergent Component of Motion Tracking”. In: *IEEE International Conference on Robotics and Automation (ICRA)*. Seattle, Washington, May 2015.
- [50] C. Knabe et al. “(Forthcoming) Designing for Compliance: ESCHER, Team Valor’s Compliant Biped”. In: *Journal of Field Robotics* ().