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DESIGN OF A HUMAN-LIKE RANGE OF MOTION HIP JOINT FOR HUMANOID ROBOTS

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ABSTRACT

For a humanoid robot to have the versatility of humans, it needs to have similar motion capabilities. This paper presents the design of the hip joint of the Tactical Hazardous Operations Robot (THOR), which was created to perform disaster response duties in human-structured environments. The lower body of THOR was designed to have a similar range of motion to the average human. To accommodate the large range of motion requirements of the hip, it was divided into a parallel-actuated universal joint and a linkage-driven pin joint. The yaw and roll degrees of freedom are driven cooperatively by a pair of parallel series elastic linear actuators to provide high joint torques and low leg inertia. In yaw, the left hip can produce a peak of 115.02 [Nm] of torque with a range of motion of -20° to 45°. In roll, it can produce a peak of 174.72 [Nm] of torque with a range of motion of -30° to 45°. The pitch degree of freedom uses a Hoeken's linkage mechanism to produce 100 [Nm] of torque with a range of motion of -120° to 30°.

1. INTRODUCTION

Since the debut of WABOT by Waseda University in 1973, humanoid robots have evolved into highly-dynamic walking machines [1, 2]. Advances in control theory, design, sensors, and computing have advanced the field from slowly walking on flat terrain to reliably walking over rough terrain with some amount of disturbance rejection. Though humanoid robots do not walk as effectively as adult humans, they are steadily advancing in their capabilities.

The DARPA Robotics Challenge (DRC) is a disaster response competition to place robots into disaster response scenarios in a human-structured environment. Originally, this competition included tasks such as climbing into a utility vehicle, climbing an industrial ladder, and traversing a rough terrain course. These events were modeled after first responder activities at disaster sites. For a humanoid robot to compete in the DRC, it needs to have similar capabilities to a person. From a physical perspective, the robot should have a similar range of motion (RoM) and set of limb lengths to a human. The Tactical Hazardous Operations Robot (THOR) is a 1.78 [m] tall, 65 [kg] humanoid robot designed to compete in the DRC is shown in Figure 1.

The hip is a three degree of freedom (DoF) spherical joint at the top of each leg. It is one of the most complicated joints in a humanoid robot. Several existing humanoid platforms use a set of three rotary actuators to drive the three DoFs [1-6]. Each actuator drives one DoF in a serial chain. They must produce enough torque and speed to drive their respective joints to allow the robot to walk and perform other tasks. These rotary actuators have a constant torque limit over their large RoM.

Humanoid robots have started using parallel linear actuators to cooperatively drive multiple DoFs in the hip [7-9]. This actuator configuration can reduce the inertia of the leg while increasing the strength of the joint. However, parallel actuators limit the joint RoM due to physical interferences. Parallel actuation with linear actuators is a simplification of the human musculoskeletal system, where numerous muscles span a single joint and work cooperatively to drive limb movement.

The lower body of THOR uses linear series elastic actuators (SEAs) to drive each joint [10, 11]. The actuators control the joints both individually through a four-bar mechanism and cooperatively in a parallel configuration. With universal joints at both ends and no linear guide restricting the motion of the ballnut on the ballscrew, these actuators are capable of driving universal joints in parallel.

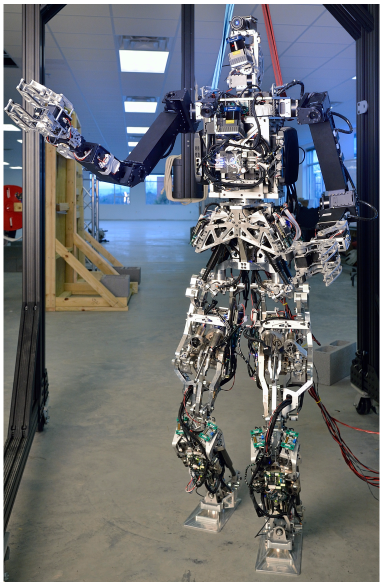

Figure 1: Tactical Hazardous Operations Robot (THOR)

Section 2 will cover the actuator configuration for the hip joint, separating the yaw and roll DoFs from the pitch. The structural members involved in the hip joint will be discussed in Section 3. Conclusions and future work will be presented in Section 4.

2. HIP ACTUATOR CONFIGURATION

Connecting the torso to the thigh, the hip is the most complicated joint on THOR. The hip is a 3 DoF joint that requires that the yaw, roll, and pitch axes all intersect at the same physical location. This joint on THOR has a large RoM, especially for the pitch DoF. The left leg RoM for the hip joint of the average human, SAFFiR, and THOR is shown in Table 1 [9, 12-14]. The average human and SAFFiR ranges of motion are presented for comparison.

Table 1: Range of Motion for the hip joint

Joint Axis		Average Human	SAFFiR	THOR
Hip Yaw	Min [deg]	-30	-10	-20
	Max [deg]	60	25	45
Hip Roll	Min [deg]	-30	-23	-30
	Max [deg]	45	23	45
Hip Pitch	Min [deg]	-135	-45	-120
	Max [deg]	20	45	30

The desired RoM for hip pitch would not be easily attained with a large amount of torque throughout the motion, so the hip was split into two separate joints with the pitch isolated from the yaw and roll. An intermediate body in the middle of the hip joint, the coxa, physically separated the two joints. Because it is the last DoF in the hip joint, the hip pitch was designed as a part of the thigh. All three DoFs still intersect at the same point, but only the yaw and roll use parallel SEAs. The distribution of the hip actuators can be seen in Figure 2.

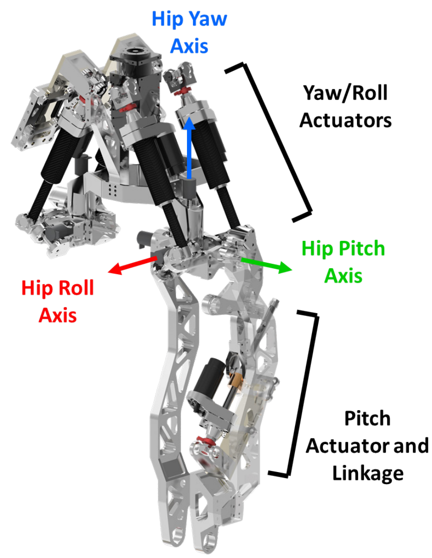

Figure 2: Hip joint actuator configuration

2.1 Yaw and Roll Actuators

The yaw and roll DoFs are driven by a pair of linear SEAs in a parallel configuration. The THOR SEA is fundamentally based on the SAFFiR SEA, but contains many design improvements to increase the output force while decreasing the overall size [10, 15]. The SEA still consists of a stand-alone actuator paired with a titanium compliant spring. A rendering of the SEA can be seen in Figure 3.

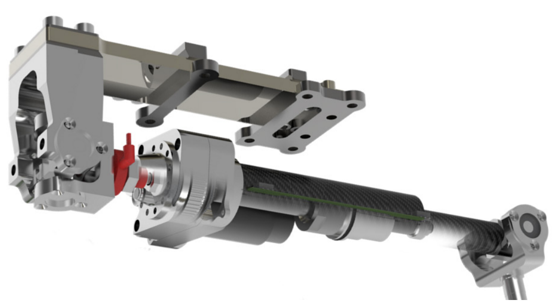

Figure 3: THOR series elastic actuator

The fundamental elements of the stand-alone actuator are still the same [10]. A brushless DC motor rotates a ballscrew through a belt drive. There is no linear guide on the ballnut, allowing for free rotation between the ends of the actuator. The structure of the robot restricts the rotation about the primary axis of the actuator. There are universal joints at both ends of the actuator and a uni-directional load cell measures the actuator force. The housing of this actuator is shorter than the SAFFiR actuator, allowing it to achieve the same RoM while occupying less space. The fixed length of the actuator, the length of a zero-stroke actuator, was the limiting factor to the hip design. The THOR actuator has a 0.111 [m] fixed length.

The actuators are placed symmetrically about the midpoint of THOR. This configuration, seen in Figure 2, was chosen for the simplicity of its design and ease of manufacture. A number of other options were explored, but all would have required significantly more complicated manufacturing to build THOR.

The fully symmetric design has two primary drawbacks. This design requires a large amount of vertical space to successfully implement. Secondly, the yaw torque produced in this design is low compared to the roll torque. In an ideal situation, the actuators would be horizontal to maximize the torque produced in both roll and yaw. However, this would require actuators with extremely small fixed lengths or wide hips. To make the actuators fit within the design, the actuators need to be angled relative to the transverse plane of the robot. This will reduce the yaw torque possible, but it will allow for actuators with longer fixed lengths. Widening the hips with angled actuators would allow for larger yaw torque outputs, but it would increase the roll torque demand for the hips.

The placement of the actuator ends was an iterative process for the hip as the design of the joint was done in conjunction with the design of the actuator. The maximum fixed length and universal joint rotations change as the ends of the actuators are moved around the torso and coxa. For each configuration iteration, the fixed lengths and universal joint rotations were compared against the actuator design to determine if a design was feasible. Using this criterion as well as the joint torques, the ends of the actuators were placed. The actuator length and universal joint rotation requirements were calculated in the same way as those of the SAFFiR actuators [15]. The front actuator length requirement is shown in Figure 4 and is summarized in Table 2. The back actuator maximum fixed length is almost the same as the fixed length of the actuator, and the front actuator determined the amount of ballscrew stroke.

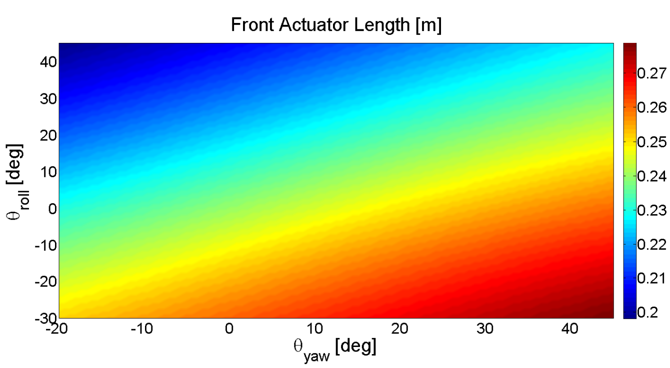

Figure 4: Front hip actuator length requirement

Table 2: Hip actuators length requirements for actuators in front and in back of the hip joint

Hip Actuator	Front Actuator	Back Actuator
Length Range [m]	0.1982 to 0.2787	0.1901 to 0.2691
Minimum Stroke [m]	0.0805	0.079
Max Fixed Length [m]	0.1176	0.1112

The universal joint designs played a critical role in the hip actuator placement. Unlike the actuators on SAFFiR, the actuators on THOR use universal joints with limited RoMs to reduce their overall sizes [10, 15]. Limiting the rotation ranges reduces the length of the universal joint. The joints were modified many times during the actuator end placement process to account for small changes to their required RoM.

The universal joints on the torso are identical to those connecting actuators to the compliant springs across the legs. Therefore, their RoM requirements were determined by examining both the hip and ankle actuators. The universal joints on the coxa need a much larger RoM to allow for the full actuator movement. Because these universal joints are much closer to the hip joint, their rotations are larger than the torso universal joints. The rotations of the universal joint on the coxa for the back actuator are shown in Figure 5, and the full RoMs for all the hip universal joints are presented in Table 3.

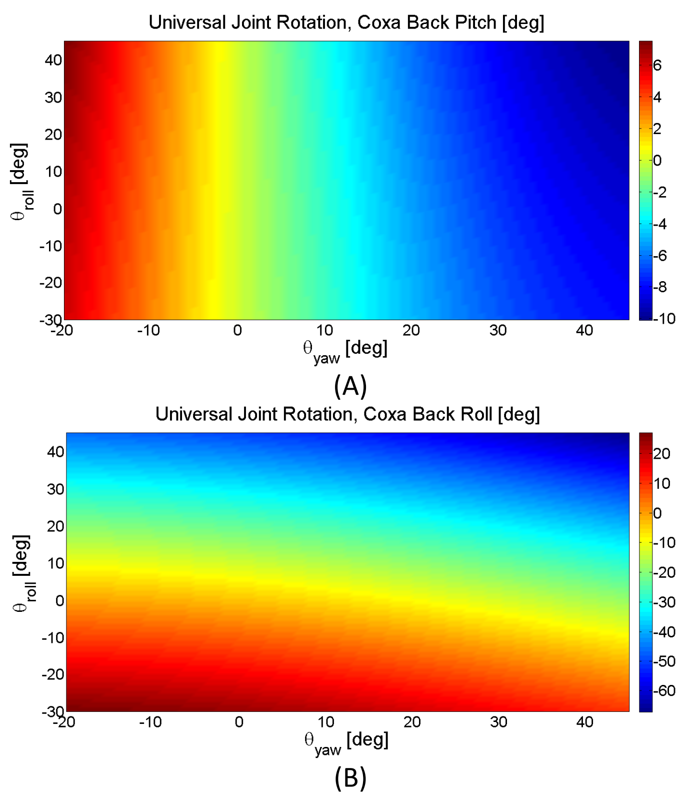

Figure 5: Back hip actuator coxa universal joint rotation requirements in (A) pitch and (B) roll

Table 3: Hip actuators universal joint rotation ranges

Hip Actuator	Front Actuator	Back Actuator
Torso Universal Joint Pitch [deg]	-7.26 to 6.43	-14.82 to 4.05
Torso Universal Joint Roll [deg]	-2.95 to 12.63	-4.87 to 3.69
Coxa Universal Joint Pitch [deg]	-17.48 to 6.09	-10.10 to 7.49
Coxa Universal Joint Roll [deg]	-61.56 to 22.47	-67.24 to 26.96

The universal joints attached to the coxa have a skewed RoM in roll. The roll DoF connects the actuator to the joint. Because of the skewed RoM, the cross gimbal is shaped like a capital "Y" instead of the traditional "+" shape. This will be further discussed in Section 3.2.

The actuators are capable of producing large amounts of joint torque in their nominal configurations. As the joint moves, the mechanical advantage for each actuator changes from the nominal positions. Figure 6 shows the maximum possible torques for pitch and roll over the ankle RoM using a pair of 2000 [N] actuators. The possible torques are calculated by simulating the torque applied by both the front and back actuators on a lever arm that rotates with the joint.

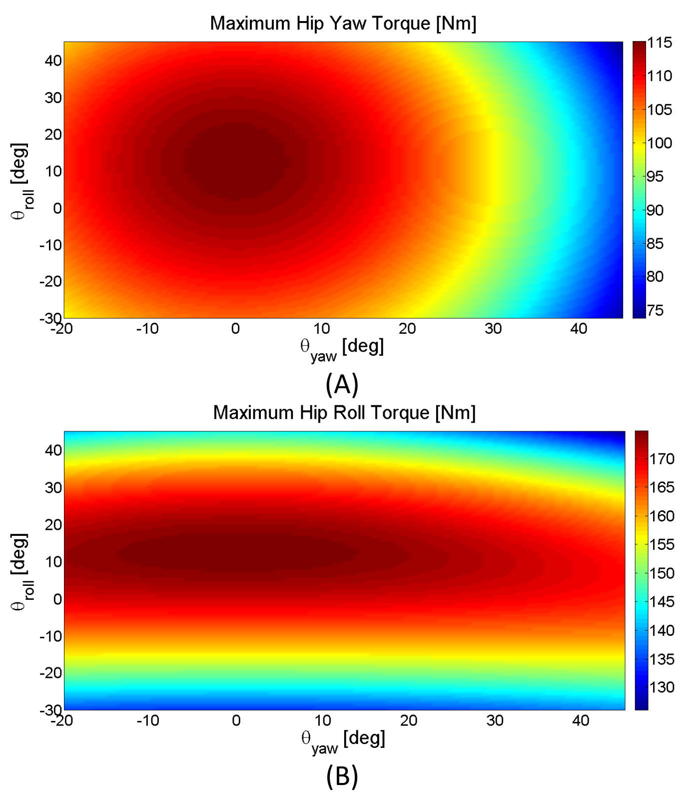

Figure 6: Maximum joint torques in (A) yaw and (B) roll

Based on the design of the joint, the yaw and roll torques are symmetric about 0° of yaw rotation. While the maximum yaw torque varies with both yaw and roll, the maximum possible roll torque is relatively independent from the joint yaw angle. Both maximum torques occur at 12.5° of hip roll. This is due to the layout of the actuators while trying to keep the overall profile of the torso as low as possible. A table of the maximum torque range can be found in Table 4. These maximum torques represent the largest and smallest peak torques achievable over the full joint rotation.

Table 4: Hip yaw and roll torque maximums

Joint Axis	Smallest Max Torque [Nm]	Largest Max Torque [Nm]
Hip Yaw	73.74	115.02
Hip Roll	125.94	174.72

As stated earlier, the maximum roll torque is more important than yaw torque. Roll torque is required throughout the walking gait and it contributes to many of the motions required for the DRC. Yaw torque is primarily used for turning the robot, which is less critical than general walking.

One feature of the SAFFiR actuators was that the 100 [W] motors could be replaced with 200 [W] motors for increased maximum and continuous forces [15]. This feature is still present in the THOR actuators, where a 200 [W] motor can be inserted with minimal changes to the robot [10]. Replacing the motors with 200 [W] versions would increase the torque capabilities of the joint to approximately 1.5 times the original amount, making the smallest max roll torque 188.91 [Nm].

2.2 Pitch Linkage Actuator

The hip pitch DoF requires a RoM of 150°. Achieving this large RoM with constant high torque is not feasible using a linear actuator in a similar configuration to the yaw and roll. As shown in Figure 6, the joint torques decrease significantly over the actuator RoM. To mitigate this problem, a linear-to-rotary linkage was used to provide nearly constant torque over the whole joint RoM [11]. Though this linkage is too large to fit at the other joints of THOR, it uses the same linear actuators as those joints.

The Hoeken's linkage is a planar, four-bar mechanism that converts rotary motion to nearly linear motion. This linkage can be configured to produce a nearly-linear output through upwards of 180° of input rotation [11, 16]. Traditionally, a Hoeken's linkage is used to convert rotation to linear motion. The linkages in THOR are used to convert linear motion to rotation [11]. This allows THOR to use the same actuators throughout the legs to produce a large RoM for the hip pitch while allowing for accurate force control at the joint. The Hoeken's linkage in the hip is shown in Figure 7.

Using a 2,000 [N] linear actuator, the Hoeken's linkage outputs up to 100 [Nm] of torque [11]. This is sufficient to drive the pitch DoF over the range of tasks in the challenge. In order to avoid interferences over the whole range of motion, the linkage pieces were designed with a non-linear shape. The three bearing part shown in green in Figure 7 is shaped like a "W" to avoid intersecting the main pitch axis of the hip and the actuator motor at -120° and at 30° of rotation respectively. Even though this shape prevents intersections over the RoM, the valleys in the "W" are not deep enough to allow a 200 [W] motor to be used with this actuator. The split at the bottom of the part is designed to fit around the ballscrew of the actuator. The two bearing part colored blue in Figure 7 is curved to avoid interference with the coxa. Its split fits around the middle bearing in the three bearing link.

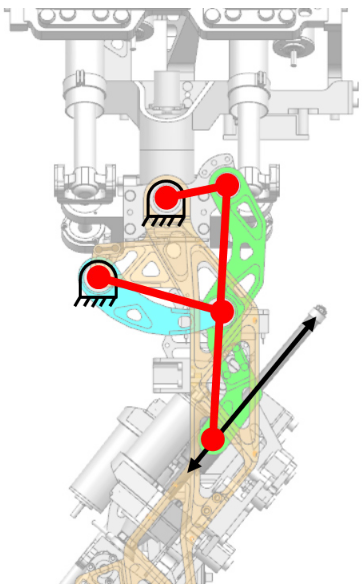

Figure 7: Hoeken's linkage in the hip

There are many methods to design parts for a planar linkage like the Hoeken's linkage with each joint in double shear. One is to place the majority of each link on the same physical plane and have the bodies split apart close to the joints. This split is shaped similar to a "Y", where most of the link is a singular part like the base of the "Y", and the joint is divided like the top of the "Y". This design method can be more compact than completely separating the linkage parts.

The hip pitch linkage is located outside of the coxa. This placement avoids interference with the torso as the hip goes through yaw and roll motions. The linkage was designed to be thin while still placing each axle in double shear by using the "Y" splitting method. Making the linkage thin increased the difficulty for any repairs, essentially requiring the whole leg to be dismantled to replace any part. A front view of the hip linkage can be seen in Figure 8.

The hip pitch joint produces motion in both the positive and negative direction, though it is heavily biased in the negative direction. To produce this motion, the actuator is partway through its travel when the leg is in a vertical position. The motion of the linkage over the hip RoM can be seen in Figure 9.

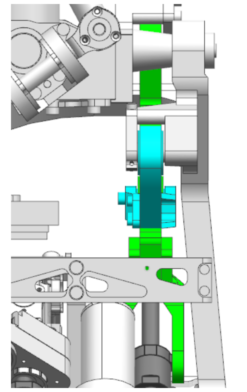

Figure 8: Front view of the hip Hoeken's linkage

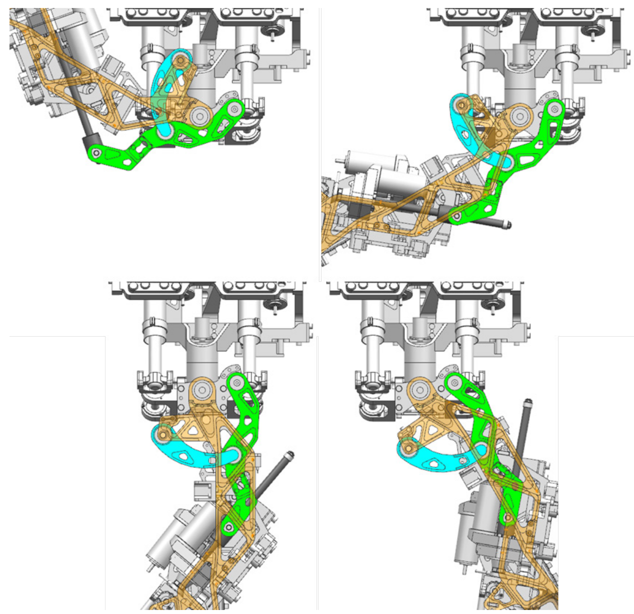

Figure 9: Hip Hoeken's linkage at -120°, -60°, 0°, and 30°

3. HIP STRUCTURE

As detailed in the previous section, the actuators in the legs of THOR span the hip joint. Between each joint is a structural body that gives THOR a similar morphology to a human. The torso connects both hip joints and the waist. Each hip joint has an intermediate body, the coxa, which separates the spherical joint into a universal joint and a pin joint. Completing the hip is the thigh, which houses the pitch actuator and Hoeken's linkage. These structural bodies also hold configurable compliant springs for the SEAs, proprioceptive sensors, and electronics. This section will discuss the structure design of THOR's hip.

3.1 Torso

The torso of THOR connects the two legs through their respective hip joints to the upper body through the waist. It houses the majority of each actuator that drives those joints as well as the configurable compliant springs for each SEA. The torso is the only body in the lower half of THOR that interacts with both the left and right legs. Therefore, it must house actuators for both legs without any interference. The symmetric design discussed in Section 2.1 requires that the actuators do not cross the medial sagittal plane of THOR.

The actuators of THOR all use identical compliant springs for their series elasticity. These springs have the same interfaces to the structure, as seen in Figure 10. The compliant springs are located 50 [mm] away from the axis of the actuator, which limits the possible interface locations for a given actuator. The interfaces were placed on the outside of the actuators to prevent parts from crossing the medial sagittal plane.

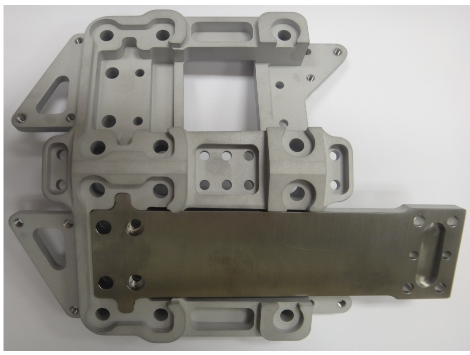

Figure 10: Compliant spring mounted in the standard interface

To place the compliant interfaces on the outside of the actuators, the torso was designed like a box. As shown in Figure 11, the left and right sides of the box are slanted to match the nominal angle of the actuators. This box is connected to the pelvis of the robot through three struts on the front and sides. The back of the box directly bolts into the pelvis.

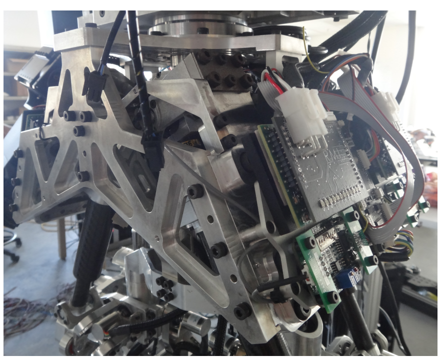

Figure 11: Box structure around the hip actuators

The pelvis is the base piece of the torso that connects the two hip joints. Each hip yaw joint has a pair of sealed angular contact bearings to accommodate the vertical loads through the joint. The hip yaw is the only joint that has large axial loads running through it. Even though the bearings are pressed into different parts, there are alignment pins in each one to ensure that their axes align.

There are a few proprioceptive sensors attached to the pelvis. The bottom of the pelvis has a set of locating pegs to align the attitude and heading reference system (AHRS) to the robot. The pelvis serves as the coordinate reference for THOR, so it is important that the inertial sensor is properly aligned to it. There is a pair of absolute rotary encoders to measure the yaw angle of each leg. The actuators for the hip require support electronics to operate. These electronics are mounted on the outside of the torso. Each side of the torso has two motor power supplies, two load cell signal conditioning boars, and one motor controller. The motor controller commands both parallel actuators for a hip joint. In addition to the actuator electronics, the torso also houses a power distribution circuit for the whole lower body.

3.2 Coxa

The coxa is an intermediate body in the middle of the hip joint. It is effectively the cross gimbal that forms the spherical joint. This intermediate body allows the hip to be divided into a parallel actuated universal joint and a linkage driven pin joint.

In order to prevent interferences with the pelvis yaw bearings, the coxa is box shaped. The outermost side of the box is the short lever arm in the Hoeken's linkage. It is spaced far from the hip axis to prevent interference when the hip moves to 45° of roll motion. An image of the coxa is in Figure 12.

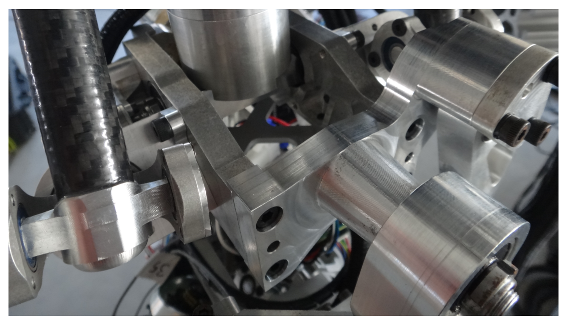

Figure 12: The coxa in the center of the hip joint

The coxa is the mounting point for the two parallel actuators that drive the yaw and roll DoFs. They mount to the front and back of the coxa through high RoM universal joints seen in Figure 13. In order to avoid part interferences, these are non-traditional universal joints.

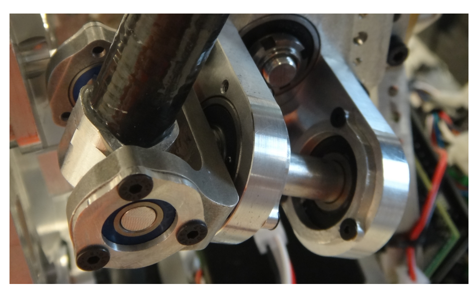

Figure 13: Universal joint connecting hip actuator to the coxa

Both of the coxa universal joints should be able to reach any combination of their maximum and minimum pitch and roll angles simultaneously. Due to the large RoM, the cross gimbal of the universal joint is shaped like a capital “Y” to prevent intersections of the two ends of the joint. Additionally, this design decreases the outer profile of THOR by not placing bearings and supports farther from the sagittal plane.

3.3 Thigh

The thigh is the final structural body associated with the hip. In addition to housing the pitch actuator, the thigh is also one of the links in the Hoeken’s linkage. It also holds the knee actuator and Hoeken’s linkage and all the support electronics for both linkage actuators.

To protect the linkages and actuators, the thigh is also shaped as an exoskeleton box. The compliant interfaces for both actuators are mounted to the back of the thigh. The outer width of the thigh was defined by the thigh Hoeken’s linkage. An image of the thigh is shown in Figure 14.

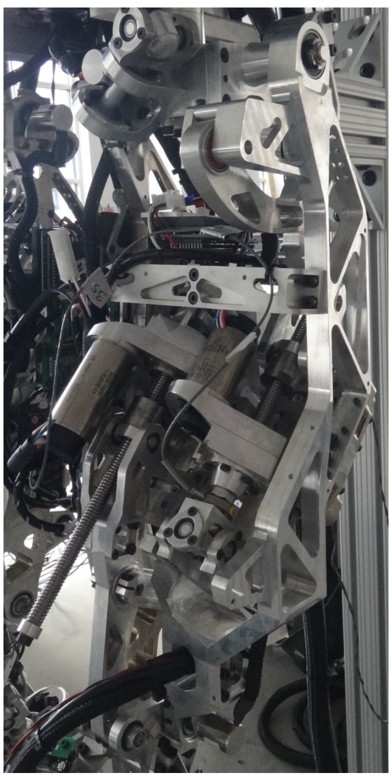

Figure 14: The thigh of THOR

One important feature of the thigh is its shape. The thigh is bent backwards from the line connecting the hip and knee joints. This shape is intended to avoid intersections with the torso when the leg pitches far in the negative direction. An empty cavity in the middle of the thigh fits the coxa during those same motions.

Similar to the torso, the thigh also houses electronics and sensors. There is an absolute encoder on each end of the thigh for the hip pitch and knee. This is the same encoder that is used in the torso and coxa to measure the yaw and roll angles respectively. There are also support electronics placed on the inside of the thigh for the actuators. Even though the electronics for the right and left thighs are physically close to one another, they will not interfere before other portions of the leg.

One consequence of the hip Hoeken’s linkage design is that the thigh must be assembled in a specific order. The links are sandwiched between the outside of the coxa and the outside of the thigh during assembly. The outside thigh bone is the first thigh part placed on the leg during assembly. Replacing components in the linkage requires a full disassembly of the thigh, and therefore, the majority of the leg.

4. CONCLUSIONS AND FUTURE WORK

This paper presented the design of the hip joint for the human-like RoM humanoid robot THOR. The spherical joint is divided into a two DoF universal joint and a single DoF pin joint by using an intermediate body. Parallel SEAs drive the yaw and roll DoFs. The yaw and roll have a smaller RoM than pitch, so it was possible to drive both with parallel actuators. This parallel configuration produces up to 174 [Nm] in roll and 115 [Nm] in yaw. The pitch DoF is actuated by a Hoeken’s linkage coupled with a SEA. This produces a peak of 100 [Nm] of torque over the 150° RoM.

The structure was built to house the actuators while avoiding physical interferences over the RoM. The torso, coxa, and thigh are all designed as box structures that surround actuators and bearing assemblies. The ends of the actuators and linkage pivots dictated the size of each structural body.

There are a few areas for further investigation regarding the hip joint. These have not been addressed by the authors, but would benefit THOR if solved.

- Because all the actuators in the lower body of THOR are SEAs, the actuator ends deflect under load. This deflection was not accounted for during the iterative search for the parallel actuator ends. Though the actuators are designed with a 2 [mm] buffer at each end of their travel, the compliant deflection will eliminate a small portion of the RoM. Solving for a revised RoM under high loads could be useful.
- THOR is not capable of reaching the three extreme ends of its hip RoM simultaneously. For example, at a yaw, roll, and pitch angle set of 45°, 45°, and -120° respectively, parts of the Hoeken’s linkage intersect with the front parallel actuator. Solving for the actual set of achievable yaw, roll, and pitch angle trios would benefit the walking controller.
- As stated above, the THOR hip cannot reach the far ends of its travel. This is similar to a human, where muscles limit the hip RoM. One area for further investigation would be the design of a hip joint that can reach the extreme ends of its joint travels simultaneously. This has been achieved in hip joints

that have a smaller RoM, but not in hips that mimic the human RoM.

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