Dynamic Step Control for Exoskeleton Stair Climbing

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***Abstract*—Lower limb exoskeletons have garnered significant attention due to their potential applications in rehabilitation for individuals with leg motor impairments. Generally, the employed pathing and control systems require the user to adjust their movements to match predefined motion trajectories. While this technology has been well researched in terms of just walking, many prototypes lack the ability to autonomously plan stair climbing. While stairs typically come in a standard size, non-conforming steps still exist and would pose a challenge to exoskeletons programmed for specific step geometries. We propose a novel trajectory-planning control scheme based on Dynamic Motion Primitives (DMP) for a lower limb exoskeleton robot that will utilize motion data gathered from human subjects to produce leg motion trajectories. These subjects will be tracked climbing up and down stairs using a motion capture system to record joint movement and angles. Using this data, we will model a control system for approaching an identified staircase and climbing the stairs. The results of this study will further the development of the exoskeleton currently under development in the WPI AIM Laboratory.**

***Index Terms*—exoskeleton, path trajectories, stair climbing, dynamic motion primitives**

Fig. 1: Model of exoskeleton

I. Introduction

Powered lower-limb exoskeletons are currently of great interest in the medical field due to their potential rehabilitative applications for patients with motor disabilities. A controller is used to obtain dynamic posture and gait planning with varying levels of precision depending on model complexity. Gait planning requires tuning predefined trajectories through trial and error, and it is difficult to tailor the system to the individual user. To overcome these challenges and to optimize the exoskeleton's capabilities, we will use human motion capture data to produce a more adjustable controller for the system.

Humanoid robotics and exoskeleton control systems [1] are two closely-related fields with a shared research focus being the stair climbing problem. While there have been significant results for motion planning on static environments, climbing stairs remains an ongoing challenge. Of the commercially available lower-limb exoskeletons, the ones with the ability to climb stairs have significant constraints, such as the inability to navigate stairs of different heights [2].

A LiDAR will be used for obtaining stair information (i.e. stair depth and height) and building the navigation environment. Segmenting the environment into planes and reconstructing the geometry into a workable format using depth sensors has been a widely studied approach [3][4].

Once a staircase is located and categorized by its dimensions, the control system needs to plan the individual motions that will bring the exoskeleton to the staircase without wasting steps and then bring them up the stairs. Various works in humanoid robotics and exoskeleton motion have utilized the DMP framework introduced by Ijspeert et al. [5]. This framework models the system as a set of differential equations representing the system kinematics modified by a non-linear component. The non-linear component represents the dynamic model of the system, which contains a set of space variables. Typically, these space variables represent the joint angles of the links of the robot [2]. The non-linear component is often learned from training examples, and various different methods for training have been investigated thoroughly [6]. A number of different methods have been used to capture training data, including motion capture [7] and recording the joint data from humans wearing exoskeletons while performing activities [5]. From the motion capture data the joint angles for each portion of the movement can be extracted and used to train the model.

Another constraint on the movement primitives for exoskeletons is the stability of the system [2]. To ensure the exoskeleton does not tip over, the Zero Moment Point (ZMP) can be calculated for each movement [2]. This constraint can be applied to each of the movements to ensure that they do not cause the ZMP to move outside of a stable range.

Additional relevant literature includes Rui Huang et al. [6], who proposed HIL (Hierarchical Interactive Learning) that consists of two learning strategies: low-level controller and high-level motion learning to learn both controllers and motion trajectories for the lower exoskeleton simultaneously. Similarly, Qiming Chen et al. [8] developed a novel model-less approach where a step length adaptation method is used to adapt variant motions of the user during exoskeleton use. Xichuan Lin et al. [2] developed strategies for lower limb exoskeletons ascending and descending discrete sizes of staircases using infrared range sensors, foot pressure sensors, and angle encoders. Infrared sensor data is used to precisely detect the stair edge and ZMP stability criterion based on the foot pressure is utilized for safety reasons. The experiment is conducted on four spinal cord injury patients to validate the proposed strategies. This work supports that these strategies are applicable to manage staircases of various sizes.

II. Project Goals

A. Obtain Motion Capture Data

Using a motion capture lab and a small custom staircase, data will be collected from participants. These participants will be gathered by responses to an email advertisement sent by the team. Motion capture markers will be temporarily attached to the individuals in designated and consistent locations for the duration of the test. The staircase will be approached and climbed by the participants under varying step height configurations following a consistent procedure.

B. Model Simulation

We will develop a simulation of the LiDAR and staircase to assist our work in developing a stair climbing control system for the exoskeleton. This will be done primarily in ROS and Gazebo.

C. Stair Detection & Path Planning

Using the LiDAR and motion capture data, we will develop control models for two distinct processes: planning steps to an identified staircase such that no steps are wasted and planning the stepping kinematics the exoskeleton will need to climb stairs of differing sizes. An A* model will be sufficient for footstep planning while a combination of motion capture marker kinematics and DMPs will be used to model the climbing.

III. Methodology

A. Coding Libraries

The kinematics of the exoskeleton will be optimized using various existing libraries like Rigid Body Dynamics Library (RBDL) and Point Cloud Library (PCL) and will be visualised using the ROS Visualization Tool (RViz). PCL [9] is an open-source library which is used to process tasks in 2D and 3D and contains algorithms for feature estimation, model fitting, and data segmentation. RBDL [10] is a robotics-centered library that allows for efficient computations of forward and inverse dynamics, Jacobian matrices, and closed-loop models. RViz [11] is a 3D visualization tool used for displaying sensory and live state data from Robot Operating System (ROS).

B. LiDAR Data

The primary purpose of this project is to develop controls for the legged exoskeleton robot, enabling the identification of the location of nearby stairs and calculating an appropriate path trajectory for the steps needed to reach the stairway. The control system will additionally use the identified stair height to plan movement trajectories for climbing the stairway. However, before this work can begin, we must collect specific data to assist in the development process. Information on the surroundings of the experimental testing area collected with the mounted LiDAR sensor and motion capture data of the kinematics of individuals climbing a set of stairs are both necessary.

Data acquisition for the surrounding area of the testing room is collected by a TiM561 LiDAR sensor in the form of a 2D point cloud representation. The device measures the distance of objects within a 270 degree range to a maximum of 10m (32.81ft). The LiDAR is attached horizontally to the side of one of the hips of the exoskeleton and measures distances in front of the robot and 135 degrees vertically above and below the forward direction.

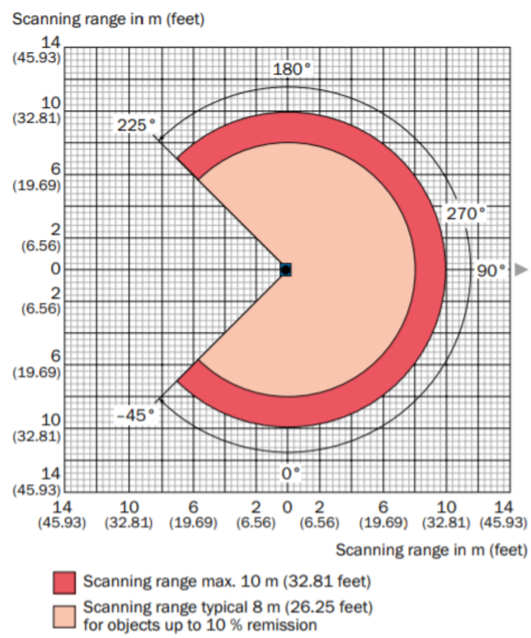


Fig. 2: TiM561 scanning range

The data is collected in point cloud form by a companion computer running ROS, which is connected to the sensor via Ethernet. The TiM561, manufactured by SICK, allows for setting up custom connections and configuring the data collection system.

To ensure proper sensor equipment function, a test was performed at the foot of a staircase. The LiDAR generated an image resembling the physical stairs when turned on, confirming that the device was working as intended.

For the purpose of this project, the stairs and the surrounding area features must be measured and collected for trajectory

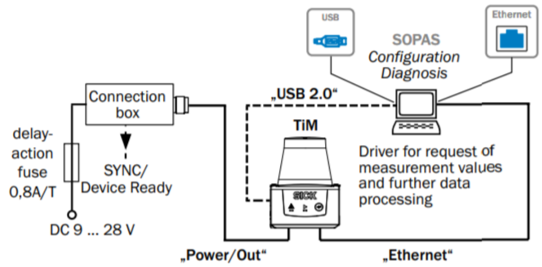
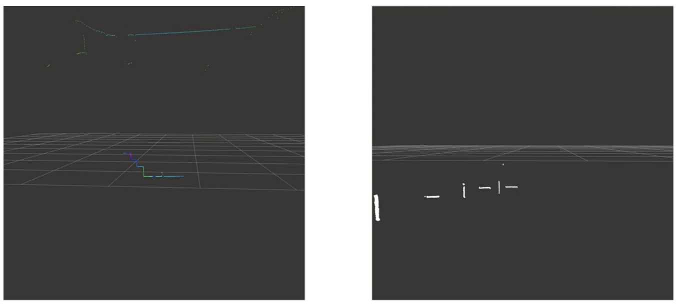


Fig. 3: LiDAR connection diagram



(a) Raw LiDAR

(b) Segmented LiDAR

Fig. 4: LiDAR Data

planning. The distance between the exoskeleton and the stairway is necessary for planning the motions leading the robot to the first step while the depth, height, and angle of the stairs themselves are needed to plan the stair-climbing motions. All of this distance data is well within the capabilities of the TiM561 as long as objects are within the typical sensor range of 8m to 10m. As proven by the minor test mentioned prior, the computer used with this sensor is capable of receiving, processing, and storing the point cloud data that the LiDAR outputs.

C. Motion Capture Data

A motion capture system will be used for the collection of gait and stair-climbing data from various test subjects of different sizes to further assist in the development of the general path trajectory control system we are proposing. Since this involves human trials, an IRB approval is required to proceed with testing regardless of its low-risk nature. Each of our team members have completed the base IRB certification requirement for our category of experiment.

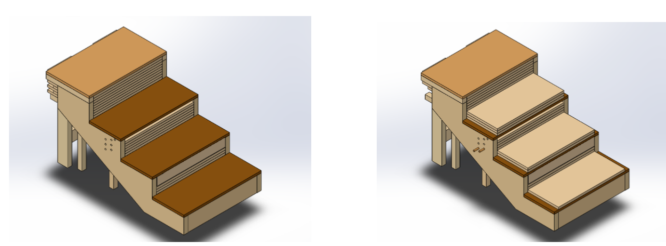
The subjects of this data collection are volunteers gained through open advertisement of the experiment. Everyone is told beforehand exactly what information is being recorded and is instructed on the process of the data acquisition taking place. Besides the motion data, age, sex, weight, height, and leg dimension measurements are all recorded as well.

The equipment being used in this phase of the work includes a Vicon commercial motion capture system, force plates placed on the floor in front of the stairs, and a video camera. The Vicon system will use slip-on markers worn by the participant to record and collect joint motion. These markers will be placed on the lower back, on each of the thighs and shanks, and on each foot, with the purpose of accurately capturing the leg movement of the subject. The force plates placed on the ground surfaces are used to record dynamic stepping forces to assist with step planning. The video camera is used for recording each subject completing the experiment.

Fig. 5: Vicon rigid body markers and force plate

Data collection will take place in the dedicated motion capture lab at the PracticePoint facility at 50 Prescott Street at WPI. The experiment itself is split into two primary actions. The first, ascending a mock staircase, has several steps. The subject will stand 2m away from and directly facing the steps and will then walk to the steps with their natural gait and climb them. They will stop at the top of the steps and the testing iteration will end. This process will be repeated with different step heights and depths.

The staircase mentioned in these trials is a modular build meant to easily change between different step heights. The stairs, constructed out of plywood, have three modular steps and a safety landing at the top with a height range of 6” to 8.25” per step. Increments of 0.75” plywood boards allow for the height change. Plywood slides are held in by dowel stoppers to prevent slippage.



(a) Slides in

(b) Slides out

Fig. 6: Modular staircase

D. Generating Path and Step Trajectories

Controls are necessary for two sets of tasks. The first of these involves utilizing the LiDAR data to provide distance information for the second task set’s path planning. The output of the TiM561 is a constant flow of two-item arrays in the form of (angle position in radians, distance), which are used to give the distance to staircase to the trajectory planning computations. Additionally, the square corner geometry of stair edges makes them more easily identifiable, allowing the sensor to locate a staircase for the initial steps of the trajectory planning process by looking for straight lines. Once at the foot of the staircase, the LiDAR is able to measure the height and depth of the stairs in a similar manner.

The second task set uses both the distance provided by the LiDAR and the kinematics data collected by the motion capture system to plan motion and path trajectories, real and simulated, for the robot exoskeleton. When markers are placed on the trial participants and the experiment is run, the output data takes the form of small marker clusters representing parts of the leg, with each cluster having their own frame of reference. By performing transformations between these cluster frames, the joint angles during walking and stair climbing are acquired.

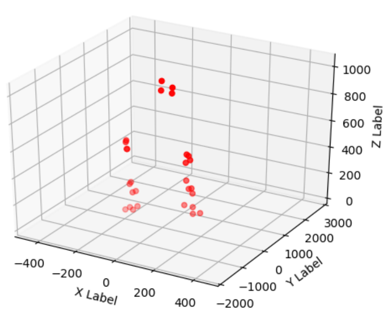


Fig. 7: Marker clusters from motion capture system

Participants begin by walking a short distance towards the bottom of the staircase. By taking the joint angle data of each subject, an average gait range and leg movement can be generated. DMPs are used to produce movement trajectories for the physical exoskeleton in parallel with the joint movements simulated with the motion capture data. Using the distance to the staircase from current position measured with the LiDAR, said distance is split into an equal number of steps based on gait average of user parameters to prevent the exoskeleton from stuttering when near the staircase. The walking motion is handled using the process discussed prior.

The stair climbing control system functions similarly to the walking system. Measured joint angles for specific leg lengths climbing stairs of specific heights and depths create a large pool of information that both the DMPs and the motion simulator use to plan the climbing trajectories. Generalizing the data into a set of commands for the physical exoskeleton allows for the comparison of the simulation and the DMP control system. If the output motion is not identical in both instances, then small adjustments can be made to the physical control system to correct any errors.

IV. LiDAR Segmentation and Visualization

A. LiDAR Data

The SICK TiM561 LiDAR device, mounted sideways on the hip of the exoskeleton, is assumed to be producing scan data in its X-Y plane. Since this scan range is in the X-Z plane of the exoskeleton itself, we adjust the incoming point cloud to match this when displayed in RViz. A simple frame transformation of the LiDAR data as a pre-processing step suffices to accomplish this adjustment.

We process the LiDAR data in two ways. One is by segmenting the scene and looking for any stairs that may be present, and the other is by projecting those stairs into the global frame for path planning.

The first step in identifying stairs is to segment part of the incoming point cloud into lines. For our purposes, we narrow the range of the scan from 360 degrees to a 90 degree slice from straight down to straight forward in the exoskeleton frame. We then utilize the RANSAC algorithm to find points that constitute a line in this scan section.

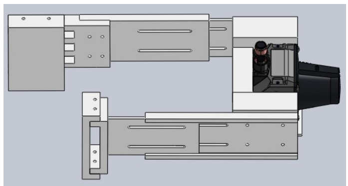
Once we have the individual line segments, we iteratively look for three neighboring segments. These three segments must meet a set of criteria to be categorized as a stair step. The first and third lines are parallel within some tolerance, the second line is normal within some tolerance to the other two, and the end points of the connected line need to be within a certain distance of one another. To compute the angles between the lines to confirm normal conditions, we utilize the normal functions included in PCL.

If we find any group of line segments that meet these criteria we will mark them as likely stairs and extract some specific information. This information includes distance from the origin to the end of the first line segment, the measured length of the second line as stair height, and the length of the third line as stair depth.

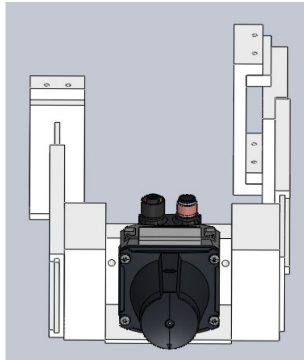
Because we only have a single plane in the data, which can rotate as the user moves, we need to track data across multiple scans. We track the lines marked as 'likely' stairs and do so across a number of LiDAR scans, currently set to three consecutive scans. This process helps smooth out the data and reduce errors.

B. LiDAR Mounting

The LiDAR mount attaches the sensor to the waist of the exoskeleton. It is designed to be extendable by a maximum of 20cm and a minimum of 4cm from the waist. This extension is done using two sliding rails, of lengths 9 cm and 15cm respectively. The extension is used for scanning for stairs when there is an obstruction at minimum extension or zero position of the LiDAR mount box from the waist. The sliders used in this design are 2-point sliders which have two grooves that are tightened after extension to give stability to the LiDAR mount. The LiDAR is mounted to the corresponding box using mount clips as shown in Fig. 8b. The material and stress analysis are to be completed later for the mounting.



(a) Side view



(b) Front view

Fig. 8: LiDAR Mounting Bracket

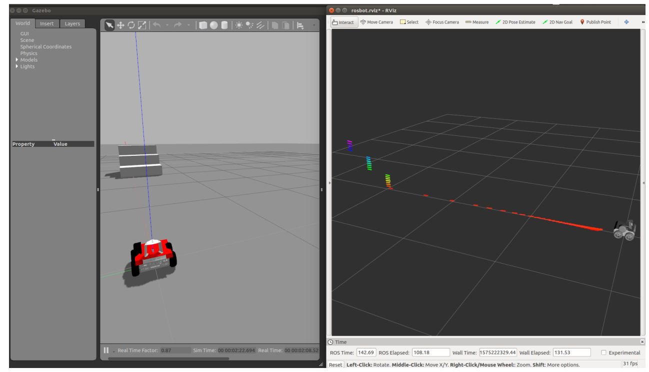


Fig. 9: Simulation of LaserScan feature and corresponding PointCloud2 message type in the simulated ROS environment

C. LiDAR Simulation

LiDAR is a remote sensing device which is used to detect the distance in the environment, for the projects case distance from exoskeleton to the staircase. It works by sending the laser pulses to the object in the domain space which is captured again as it returns backs to the sensor.

To simulate the environment consisting of stairs and laser scan functionality, a simulation model environment is built in the ROS. The obtained laserscan is further converted to PointCloud2 data type. Point cloud data are a representation of the X, Y and Z points in 3D space which represent a feature or attribute like distance, points in the feature space. The visualization data can be segmented and filtered out using a ROS node to obtain point cloud data relevant for applications like creating a surface.

The simulation involves developing a sample environment, rendering sensor model, using RViz and Gazebo and publishing the PointCloud2 messages. The laser scan is used to replicate the LiDAR functionality. The simulation environment is made in Gazebo and the laser scan is fixed on a sample robot in the environment frame. LaserScan messages contain information that can be easily fit to format into suitable data type like Point Cloud messages. The map is simultaneously built in the RViz as the scan operation is ongoing. The data is published to LaserScan message by use of Publisher and scan message type.

The Point Cloud messages are published in the Rviz environment using a node written in Python language. This is done to visualize the LiDAR sensor and to asses the obtained data in a suitable readable format. Fig. 9 shows the laser scan and corresponding PointCloud2 message type in the RViz and Gazebo window.

V. Motion Capture Data Acquisition

A. Stair Construction

The wooden three-step staircase was built for approximately $275. It deviates from the original planned 3D model in its supports; the original supports were 2x2 wood supports, but while assembling, it was clear that these parts would be inadequate for large weights. Instead, each step is supported by two 3/8" steel rods. The back legs were also reinforced with another set of 2x4s. Under the heaviest step-height configuration it can support approximately 300lbs, but it can likely support more weight. Rails were also added to the design as a requirement from the IRB's feedback. These rails are bolted on with two screws each and can be removed as needed for transportation.

As originally intended, the staircase allows for four different step height configurations. Physical stops were implemented for each configuration in both directions parallel to the stringers to prevent them from slipping. Also, the fourth step is not intended to be a step. It is only intended to house the height adjustment sliders for the 3rd step and has no supports because they would collide with the sliders.

The materials used in the staircase's construction were white pine for the balusters, support legs, and plywood step sliders. The stringers were cut from Douglas fir, main steps from oak plywood, and the hand rails from red oak. The completed staircase without the step height adjustment sliders can be seen in Fig. 10.

B. Vicon Data

We determined that the new Vicon system at the PracticePoint facility would suit our data collection best. To have a list of participants ready for when we began testing, we sent an email out to the undergraduate students as well as the robotics department outlining the study and advertising the opportunity to participate. We obtained over twelve participant email responses in total.

Before we can collect data from our participants, we must understand how to use the Vicon system effectively. Thus, we began initial testing using one of the team members as an example participant. We researched which locations on the body the Vicon markers must be placed, as well as which biometric measurements would be required. After placing the markers in the required locations for the lower body gait model preset on the Vicon system, as shown in Fig. 11, we attached the rigid body markers from Fig. 5 to the participant's lower

Fig. 10: Completed staircase without sliders

Fig. 11: Vicon markers on team member participant

back, thighs, shanks, and feet, to define those regions as rigid bodies in the model.

We also collected the participant's required biometric measurements of leg length, knee width, ankle width, height, and weight. We then had our participant leave the room so that we could calibrate the Vicon system's cameras without the markers interfering with the calibration. The testing area in PracticePoint is shown in Fig. 14, with the wooden staircase, the force plates on the floor in front of the staircase, and the Vicon system cameras.

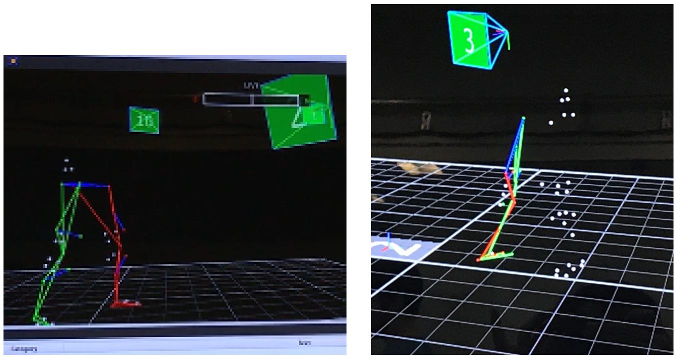
Once the cameras were calibrated, we had our participant walk into the range of the cameras to capture the markers so we could assign them properly. We connected the joint markers in the Vicon model software in one group and rigid body markers in another group, initially having only a few connections, shown in Fig. 13a. We then built the model to capture our participant's movements. Once we confirmed that movement was being captured, we set up the staircase at the end of the force plates on the floor of the motion capture studio in PracticePoint and placed rigid body markers on the leftmost side of the top of each step. We had our participant start at the edge of the Vicon system's effective range, then walk forward over the force plates up to the staircase, then ascend the staircase at which point we would stop capturing the data. We found from the first three trials that we had not defined and connected the markers in the software well enough, causing the model to break frequently, as shown in Fig. 13b. Once we fully-defined the model it moved smoothly and we could obtain useful data.

Fig. 12: Vicon lab setup in PracticePoint

VI. Trajectory Planning

A. *Walking Simulation*

To simulate a walking gait, the following approach was taken. Given a distance to stairs, stair height, and stair run lengths, step positions are planned for each foot in a path to reach the top of the stairs. Using inverse kinematics [12], the joint angles for the desired start and end foot positions for a step are calculated. A set of start and goal joint angles are sent to the set of leg DMPs to obtain the trajectories to perform the stepping motion to the goal position. Forward kinematics on each set of joint angles in the trajectories are calculated so that the legs can be plotted. The individual components that comprise the simulation will be elaborated on in the following sections. The results of the walking simulation



(a) Initial connected model

(b) Initial model broke during rebuild

Fig. 13: Vicon lower-body kinematics model

Fig. 14: Vicon lab setup in PracticePoint

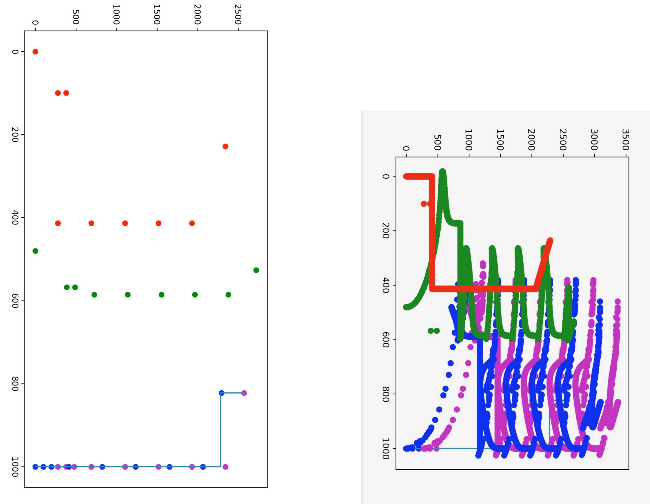
are color coded, in which red is the hip, green is the knee, blue is the heel, and purple is the toe. The figure shows the system walking upwards, with the horizontal-axis indicating the forward motion and the vertical axis indicating the vertical motion. Note that the ground plane is at the 1000 mark in the horizontal plane. This is due to the constraints of the equations used in our inverse kinematics that will be explained in the kinematics section.

B. Step Planner

We decide where to set the next foot position in the walking gait by calculating the step distance the subject would take. We define the subject's stride by taking their leg length multiplied by 0.413. Based on the distance to the stairs we shorten or lengthen the stride to make all steps of equal length. For placing steps, we place the foot on top of the next stair, with the toe located at a point at 75% of the depth of the stair. The steps only set the foot location to the desired goal position and the hip position to a displacement based on the average distance between the toes.

C. Forward and Inverse Kinematics

After we determine the goal location of the foot. We obtain the resulting joint angles by calculating the inverse kinematics



(a) Planned Steps

(b) Step Trajectories

Fig. 15: Walking Simulation

required to reach the goal position. We used the inverse kinematics solution provided in [12], in which the hip is required to be at the origin for calculations to function properly and the legs must be on a coordinate plane in which the x-axis represents the vertical axis of the legs and the z-axis represents the horizontal axis of the legs. This set of inverse kinematics allowed us to calculate the inverse kinematics of the whole system using only knowledge of the foot location, hip location, and segment lengths of the legs, since we can assume that the angle between the foot and the ground is always zero at each start and goal position of a walking or stair-climbing gait. Thus, we modified the rest of the system to plot with respect to the required coordinate axes of the inverse kinematics functions.

The forward kinematics were determined initially using the standard x-z plane and using geometric calculations due to the 2D planar nature of the lower-body kinematics system of the exoskeleton. Once the inverse kinematics were implemented, however, we realized that we now had to unify all calculations onto the same set of coordinate axes. To achieve this goal, we transformed all of the forward kinematics calculations to match the new x-z plane required by the inverse kinematics functions and put the staircase on its side such that when the legs walk up the wall, they also reach and climb the staircase as intended.

D. Dynamic Motion Primatives

Dynamic Motion Primitives (DMP) are an alternative method to achieve complex trajectories without deriving a model using physics-based methods [13]. DMPs are 1-dimensional models that can be trained using a reference trajectory. In this project, there were two methods to create DMPs, depending on whether taskspace or joint space is desired. If taskspace was desired, one DMP per axis per joint would be needed to represent the trajectories of each joint. However training the DMPs in joint-space would reduce the complexity by only requiring one DMP per joint and would be easier to translate to feed to controllers for the physical exoskeleton. Using our collected Vicon trial data, the joint angles for the hip, knee, and ankle of each leg were extracted into a CSV file. This data was parsed such that only the angle trajectories of individual steps were saved. These trajectories were used to train the six DMPs. The DMPs were trained using functionality from Nathaniel Goldfarb's DMP Library. The DMP object that was developed can take training data for walking and stair climbing steps for both legs and generate DMPs. Then, trajectories can be created for a start and goal position, specified as two sets of six joint angles. An example of a trained DMP trajectory can be seen in 16, which shows the DMP of the left knee. The DMP was given the same start and end angle position as the trained trajectory and it produces a similar curve. It deviates by 6 degrees in the beginning, but this is not significant deviation that would cause an error with walking.

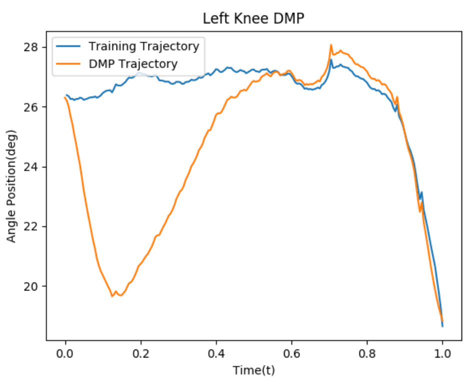


Fig. 16: Trained DMP trajectory vs Reference Trajectory

VII. Work Conclusion

Project work was distributed evenly among team members to ensure that each individual was actively participating in group work. The results of this semester's efforts as well as the members assigned to each task are listed below.

1) ***Task:*** Get IRB certification to conduct research on human subjects in motion capture lab
(Albert, Brian, Richard, Lakshay)
Dependencies: IRB response, staircase completion, IRB training for all team members
2) ***Task:*** Build the staircase that will be used in testing
(Richard)
Dependencies: Woodworking hardware and expertise
3) ***Task:*** Establish the connection between LiDAR and the data handling system
(Albert, Brian, Charles)
Dependencies: Power supply for LiDAR
4) ***Task:*** Vicon user testing/data acquisition
(Albert, Charles, Lakshay, Nagarjun, Richard)
Dependencies: Vicon training, staircase completion, IRB approval, sending participant request email and acquiring participants
5) ***Task:*** LiDAR data acquisition, line segmentation, and visualization
(Albert, Brian, Charles, Richard)
Dependencies: Accessible staircase for workable LiDAR data
6) ***Task:*** LiDAR simulation in RViz and Gazebo
(Lakshay, Nagarjun)
Dependencies: ROS LiDAR library
7) ***Task:*** Design LiDAR mounting bracket
(Nagarjun)
Dependencies: LiDAR 3D model or dimensions, Nathaniel's exoskeleton design and dimensions
8) ***Task:*** Develop step planning model for approaching staircase without partial steps at end
(Richard)
Dependencies: LiDAR scan data, accessible staircase, Vicon motion capture data, exoskeleton kinematics
9) ***Task:*** Develop control model for climbing stairs based on individual stair parameters using DMPs and motion data from motion capture
(Albert, Brian, Charles, Richard)
Dependencies: LiDAR staircase data, Vicon kinematics data, exoskeleton dynamics/kinematics

A. Future Scope

1) ***Task:*** AMBF Implementation
2) ***Task:*** Extend step planning for obstacle avoidance and non-flat surfaces
3) ***Task:*** Design hips for the exoskeleton that allow for three-dimensional movement

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