Interactive Social Robotics Deep Learning Imitator

Digital Copycats

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Senior Design Project

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Purpose

Dr. Adham Atyabi of the University of Colorado, Colorado Springs (UCCS), Electrical and Computer Engineering Department (ECE) has requested the senior class of 2021 engineering students to begin development of a social robot. As discussed with our UCCS customer, this social robot will enhance social interaction and capability among individuals who may need medical assistance or rehabilitation services. The core capabilities of this project can also be extended to other applications with the design of further enhancements and features from future engineering students and faculty.

Project Description

The social robot will be an upper-body humanoid robot placed on a flat hard surface. This robot will have human-like movements of the torso only, and therefore be limited to only human-like torso degrees of freedom. Humanoid robot will monitor human subject's movements and mimic those movements in real-time. The robot shall only mimic movements of the torso and will not have indication of auditory or visual response other than the movements themselves. Later enhancements such as legs and moving fingers have been discussed with the customer and will be developed through customer guidance and need.

Project Background

For further work our client would like to utilize our robot in additional research on the use of humanoid robots in helping those with Autism. Hence the background research is on an interactive learning method with the use of Humanoid Robots for teaching children with Autism. While utilizing functions to assist in areas of socialization, communication, and playful behavior through robot-based intervention. The review *Evaluation Implementation of Humanoid Robot for Autistic Children* goes through different teaching methods for Autistic children. The method that was used more often and had remarkable results was the humanoid robot. In their research they found that the child can interact with the robot easily and quickly because they deal with the robot as a game which could improve their emotional, social, and mental skills. The suggestion is to use robots as a solution to play a critical role in responding to robots and improve those skills. The second article *Humanoid Robot NAO Interaction with Autistic Children of Moderately Impaired Intelligence to Augment Communication Skills* presents findings from a pilot study on the interaction of autistic children with the human-robot interaction (HRI) modules executed by the Nao Robot. The result showed that 4 out of the 5 children tested exhibited a decrease in their autistic behavior. This outcome indicates that the NAO robot was able to attract the children's attention, keep each child engaged with the robot during interaction and give a positive impact on the children's communication behavior.

Major Components

The social robot will consist of the following major components:

- Robotic Structure (3D Manufactured)
- Actuators
- Motor(s)
- End Effector(s)
- Control System(s)
- Onboard Computer(s)
- External Computer(s)
- Optical Sensor(s) and Hardware
- Power Supply(s)
- Camera(s)
- Software Program(s)

Subsystems

The social robot will consist of the following general robotic subsystems:

- Mechanical
- Electrical
- Software

General Design Requirements

This section outlines the high-level design and operational requirements discussed with the customer. All requirements herein have been reviewed and include future enhancements for the social robot as requested by the customer.

1. The robot shall be constructed to resemble basic humanoid torso features, those include:
   - Waist
   - Abdomen
   - Chest
   - Left/Right arm
   - Left/Right hand w/fingers
   - Head
2. The robot shall be constructed from 3D printed material, computer hardware, and software.
3. The robot shall be able to move at locations on the torso in relation to human capability, this includes areas such as:
   - Shoulder
   - Elbow
   - Wrist
   - Finger joints
   - Neck
4. Software will be developed using in-house coding methods and/or open-source material.
5. The robot shall, using optical sensors, determine the pose and movement(s) of a human torso subject and replicate with a high degree of accuracy.
6. The robot shall utilize deep learning models to train and autonomize the replication process with no supervision.

Standards

In compliance with IEC 860601 specific to medical robots for basic safety and essential performance:

- The essential performance shall pose no unacceptable risk to a patient if motion control of the device has performance degradation.
- When in motion and within reach of people the robot shall not present an unacceptance risk.
- Risk control applicable to mechanical hazards including a risk control measure.
- Torso was designed to support the robot in all its movements.

In compliance with ISO/TC 261 specific to the international standardization committee on additive manufacturing:

- Material extrusion-based additive manufacturing of plastic materials.
- General principles — Standard practice for part positioning, coordinates and orientation.
- Qualification principles — Classification of part properties for additive manufacturing of polymer parts.

- Environment, health, and safety — Consideration for the reduction of hazardous substances emitted during the operation of 3D printer in workplaces.

Requirements Analysis and Description

This section describes the core pillars of this robotics project.

Customer's Needs

A robot capable of imitating upper body movements from a demonstrator.

Customer's Wants

A Poppy Torso with an OptiTrack camera system that utilizes machine learning models to track targets placed on a demonstrator.

Project Boundaries

The project's boundaries include the allotted time given to complete project goals through the phases of development while adhering to the project scope.

Real-World Considerations

e.g., smooth movements, durability, and design complexity creep.

Requirements by Subsystem

The following sections and subsections will detail subsystem requirements. The following outline was used to clarify our objectives.

- Overview
- Problem statement
- Operational description
- Requirement specifications
- Design deliverables
- Preliminary system plan
- Implementation considerations
  - Service and maintenance
  - Manufacturing
- Attachments
  - Studies
  - Relevant code and standards

Mechanical

The mechanical systems of this robot include structural mechanisms that will allow the robot to interact and perform tasks under various weights and pressures of the environment and the robot itself. The mechanical system will comprise of material that is available to the students' either through personal equipment and/or campus facilities. The robot's mechanical system will be manufactured using either preexisting structural CAD drawings or designed by the team.

It is unclear if the customer is knowledgeable of the mechanical properties of the structure, but they are (somewhat) frontier. The customer has recommended the use of 3D printing to satisfy the structural requirements of this robot. 3D printing has been heavily considered, albeit files have been provided for use. Project goal of 3D printing a social robot is a recent development with little case study available. The customer does have experience with preassembled social robots, so the recommendations by the customer have been taken with high regard.

Boundaries:

- The robot is not required to move from its stationery location.
- The robot is not required to perform any actions surpassing that of human ability.

Weight:

- Weight needs to be minimized to reduce stress on 3D printed structure as well as not maxing out torque on servos.
- The robot will be stationary on a tabletop.
- The robot should have portability in mind if the robot is to be moved to another location.
- Will be 3.5 kg (7.7 lb.) or under (weight of poppy with legs).

Standards:

- Refer to section "Standards" for ISO/TC 261

Size:

- The size is to be approximately 1/3 of that of a human adult (child sized).
- Proportions are adult, not child.

Location:

- Indoors

Power

- N/A

Operating conditions/life:

- Virtually unlimited
- The structures do not rub on anything.
- They are directly attached to the servo horns.
- Any wear would be where the limbs make contact on the built in stops if a joint is hyper-extended.
- The weak points are the thin/small elements of the structure.
- They are prone to breakage/delamination with lesser amounts of force (if printed using FDM, SLS prints would be more durable).
- Ideally the points are not subject to these forces.
- The structural parts are open-source 3D printable.
- Any broken pieces can be easily replaced.

Real-World considerations

- The robot need not pose a danger to others or itself.
- If there are errors that cause the robot to move at a high speed, it should not cause damage to itself nor cause harm to any nearby humans.
- Low weight and high strength structure should limit damage.

Real-World influences on specifications

- Cost
- Ease of manufacture
- Durability of structure

- Weight

Input/output analysis

- N/A

Interface preview (subject to change)

Figure 1: Poppy Torso

Electrical

The electrical subsystem of this robot includes its power, motor, and computer attributes that will enable the mechanical structure to move utilizing computer software and sensor data. The customer is both knowledgeable and in other areas frontier regarding the electrical architecture of this robotic system. There are a few other projects that have worked on tracking human motion for translation into robotic mimicry, but there is very little case study or open-source material available. The customer appears knowledgeable about the electrical properties the robot requires.

Boundaries:

- Robot needs to move as fast as a human.
- Robot needs to move fluidly like a human.

Weight:

- Weight needs to be minimized to reduce stress on 3D printed structure as well as not maxing out torque on servos.
- Cable lengths should be minimized.
- Any components (i.e., microcontrollers, processors) should be placed as low on the robot as possible to lower center of gravity to prevent tipping and to reduce stress on upper portions of torso structure.

Standards:

- Refer to section “Standards” for IEC 860601-1

Size:

- Servo and PCB circuitry should be small enough to fit into the child sized robot profile.

Location:

- Indoors

Power:

- Wall power likely.
- Battery power is possible, but not necessary for the purpose of this project.

Operating conditions/life

- Weak point is the potentiometer encoder in the AX-12A servo.
- Lifetime for the pot is difficult to determine.
- The next weak point is the DC motors in the servos.
- Operating lifetime is between 1000 – 3000 hours.
- Both problems are easily solved by drop-in servo replacements.
- Someone with sufficient knowledge of servos and small electronics repairs could fix the servo at a lower cost.

Real-World considerations

- The robot need not pose a danger to others or itself.
- If there are errors that cause the bot to move at a high speed, it should not cause damage to itself nor cause harm to any nearby humans.
- Code could be implemented for failsafe protections.

Real-World influence on specifications

- Cost
- Maintenance
- Weight
- The customer requires the robot to replicate human motion.
- This has speed and resolution considerations for the servos.
- Resolution is not translatable to human motion so the highest resolution possible should be used to avoid jerking motion.
- Average human speed is surpassed by some servos.
- Fastest human speed is not matched by servos, but the robot is not required to perform at sports/Olympic level speed.

Input/Output Analysis

- Input to servos will be based on output from visual elements.
- There is also a feedback loop from the motor encoders.

Interface preview (subject to change)

Figure 2: Servo Motors

There are several requirements and system design aspects to consider regarding the optical tracking camera system and the robot from the customer. The customer is knowledgeable regarding the application of the robot; this includes robotics from a mechanical and electrical perspective, but also from a software perspective of applied computer algorithms such as machine or deep learning. The customer understands the requirements involved for this project as well, which involve optical tracking between a robot and human subject with a high level of fidelity. This involves specific hardware and software requirements related to the optical tracking system. The optical tracking camera system must work together with a robot (easily integrate with hardware and software); track human subject movement through markers with high fidelity; and the system must be able to receive and export motion capture data in a useable format for the robot to mimic the movement of a human subject.

The optical tracking system must be able to integrate with the software and hardware that is selected during the design process of the robot. Several parameters that must be kept in mind are the ease of integration, overall size, speed in terms of frame per second, latency, internal processing speed, resolution, and data/file format. These considerations must be kept in mind during the design process as the camera is the single source of data collection and transformation to ensure the goal of this project is reached. Several boundaries and conflicting needs regarding this point involve the interrelation of camera hardware, software, and project budget.

The boundaries conflicting needs of the optical tracking system stem from camera specifications common to applications such as robotics or virtual reality systems where accurate motion capture data is desired. Ideally, an associated software development kit (SDK) is preferred or a program that would allow the camera to be used for marker labeling and processing; however, these are typically costly. Several SDKs have also been built in pre- and post-processing involved that may not be available to be customized by the user. This is an important requirement given that the machine learning algorithms developed by the team must be able to apply the collected data and the exported data must be in a useable format. Another component to consider in this realm is if the optical cameras have an SDK or software platform that allows for manual marker labeling based on the markers placed on the human subject. This boundary involves being able to individually label each marker to its respective joint once the data is collected, and then be able to feed the labeled data to the computer algorithms developed by the team so that the robot can mimic the movement of the human subject.

For the project goal to be met, the optical camera system must aim to meet the test standard created by the National Institute of Standards and Technology (NIST). This standard evaluates the optical tracking system's ability to determine the position and orientation of the subject, or its pose involving six degrees of freedom (up, down, right, left, forward, backward, pitch, yaw, and roll). This test involved moving two subjects forward and backward, and right and left, and turning it three ways relative to its original path. This test allows for x-, y-, and z- coordinates as well as the pitch, yaw, and roll. An important standard to keep in mind from the NIST standard is to place the markers at a predetermined distance apart from the other to calculate and compare the accuracy based on the measured distance between the marker points. This project will base its testing methods from the NIST test standard to gauge optical tracking accuracy.

The optical tracking system must have requirement specifications with the context of the robot and project in a university setting. The following is a table listing camera requirements specifications considered for this project. The information under the datum column was collected from a survey of research involving several types of optical camera tracking systems with several values being commonly seen specifications and several being maximum values such as the video resolution or field of view. The target range column is developed requirements based on the scope of this project, with the two primary real-world considerations of the budget, size of the robot, and testing environments. These real-world considerations influence the parameters of the optical camera system typically in a downward way; for example, given the smaller size of the robot, a smaller and lighter camera is required. Additionally, given budget considerations, parameters such as video and still resolution and frame rate are lower given the direct correlation of these parameters with a lower price.

Table 1: Optical Camera System Design Specifications

Parameter	Unit	Datum	Target Range
Quantity	cameras	2 or more	1-2
Size (H x W x D)	in	3 x 3 x 3	< 2.5 x 2.5 x 2.5
Weight	g	500	350
Video Resolution (W x H)	pixels	5120 x 5120	1280 × 1024
Still Resolution	MP	8	1.5
Frame Rate	FPS	240	120
Power Source	cable type	PoE/power cable	PoE
Accuracy	mm	+/- 2	+/- 4
Input/Output Interface	port type	GigE/USB 2.0	GigE
Data Format	data type	(X, Y, Z)/6DOF	(X, Y, Z)
File Export	file type	CSV/C3D/FBX/BVH/TRC	CSV
Latency	ms	<10	<5
Capture Distance	m	25	<5
Field of View (H x V)	degrees (°)	67 x 37	56 × 46
On-Board Marker Processing	N/A	yes	yes
Marker Support	N/A	passive/active	passive
Number of LEDs	LEDs	170	

Although several tracking cameras were researched along with several robots used in similar settings and applications, a good portion of the research thus far was dedicated to investigating the OptiTrack system for the specific project needs of optical tracking between the robot and human subject with a high level of accuracy. This camera system was highly recommended by the customer and team advisors. This camera system influenced the preliminary system design and test plan which is to track absolute position over time with no location discrepancies having a greater mean error than 5 mm, partly due to the +/-1 mm 3D accuracy of the OptiTrack camera. Furthermore, from preliminary research, the target range column in the requirements specifications above was developed mostly from the values seen with the OptiTrack camera system and with the project scope in mind.

Regarding the optical tracking process, the camera is equipped with an infrared (IR) pass filter in front of the lens and a ring of IR LEDs which illuminate the human subject who will have retro-reflective markers or tracking balls placed on human joint positions. The incoming data is internally processed with the camera system via on-board marker processing and calculates object data in 2D marker position in image coordinates, but the capability is there to reconstruct 3D data, manually label markers, and apply the team's developed learning algorithm software to the obtained data. One of the considered python libraries, PyPot, is also capable of OptiTrack integration with the robot's servomotors; however, more research needs to be done before an optical tracking camera is selected for our project.

Software

One of the biggest pieces of the software requirements for our project is the use of Machine Learning. Using machine or deep learning, our robot will need to:

- Preprocess input data
- Train using learning models
- Store learning data
- Deploy learning data

The transition from camera footage to software to robot movement is made possible by machine learning. Through forward kinematics, we can calculate positions in three-dimensional space of joints and angles. Several algorithms may be required along the way. Major machine learning algorithms and their purposes are shown in the table below.

Table 2: Machine Learning Justification

Algorithm	Purpose
Regression/Prediction	Predict continuous values
Classification	Predict a set of items' class or category
Clustering	Structure data
Association	Associate co-occurring items
Anomaly Detection	Discover abnormal activities
Sequence Pattern Mining	Predict next data events
Dimensionality Reduction	Reduce the size of data to extract only what is needed
Recommendation System	Build recommendation engines

Because machine learning is an intricate topic, there are hardware specifications that our team will keep in mind. For GPU, our project will require on that has a good cost/performance, enough memory, and good cooling. Cooling is important because temperature issues are not uncommon and can cause the GPU to become slower and die faster. While cooling and cost/performance are subject to debate, memory and memory bandwidth are important to keep specific numbers in mind. Typical values for machine learning GPU's are included in the specs table. These values were selected due to the type of project we will be creating. Using neural networks for video requires at least 24GB of memory and reinforcement learning requires at least 10GB. Other types of projects require even more memory, but these do not matter for the scope of our robot. When it comes to RAM, a common misconception is that faster is always better. However, the focus on RAM needs to be on size. While the size will not directly impact the machine learning performance, it will certainly affect the GPU code. At a minimum, our RAM will need to be the size of the biggest GPU. The minimum RAM requirement of 8GB might get the job done, but most experts recommend at least 16. The biggest concern for CPU is that it supports the GPU. The impact on the performance of the CPU will depend on the preprocessing strategy, as this is the main purpose of this. Experts typically recommend at least a 7th generation with 4-16 PCIe lanes.

Table 3: Machine Learning Hardware Specifications

Property	Unit	Value/Range of Values
GPU Memory	GB	10+
GPU Memory bandwidth	GBs/second	200-484
RAM	GB	16
CPU	PCIe lanes	4-16

Once hardware requirements are met, there are software specifications to adhere to as well. Machine learning algorithms fits into two categories: Supervised and Unsupervised Learning. Supervised learning is used when some knowledge of expected values is known. The goal outcome of this type of learning is to create a relationship function between input and output data. On the other hand, unsupervised learning is intended to approximate the already existing structure within data. Determining which type of learning to use is an essential requirement as it can greatly impact results. It is possible to use both types of learning, especially because our robot will copy movements first based on videos, and later in real time.

There are existing machine learning libraries that will be helpful for our project. TensorFlow and Pytorch are the most popular libraries used by developers and they contain minor differences. Also, of use will be Ski-kit Learn, a library specifically for deep learning, NumPy, a library that creates arrays for data, and PyPot, the Poppy Robot library that controls motors and sensors. Each of these libraries are either developed specifically for Python or can be easily integrated with it. Libraries are required for optimization of data visualization as well as teaching the robot to move as instructed.

Our machine learning software will span between the computer we choose, the robot, and possibly the cloud if we so choose to use this option. In our research into machine learning, it is crucial that the scope of the project is kept in mind past what our team will do. While our interactions with the robot will only include movements from camera footage, the goal is real time movement copying. The robot may need different types of algorithms and machine learning.

Although several tracking cameras were researched along with several robots used in similar settings and applications, a good portion of the research thus far was dedicated to investigating the OptiTrack system for the specific project needs of optical tracking between the robot and human subject with a high level of accuracy. This camera system was highly recommended by the customer and team advisors. This camera system influenced the preliminary system design and test plan which is to track absolute position over time with no location discrepancies having a greater mean error than 5 mm, partly due to the +/-1 mm 3D accuracy of the OptiTrack camera. Furthermore, from preliminary research, the target range column in the requirements specifications above was developed mostly from the values seen with the OptiTrack camera system and with the project scope in mind.

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Team Organization

The initial team of Spring 2021 consists of 6 students with diverse backgrounds within the ECE department. All fields of study have either been a major, minor, or overlapped with other core courses. Those fields include but are not limited to Computer Science (CS), Computer Engineering (EE), Data Analytics & Systems Engineering (DASE), and Electrical Engineering (EE). The following table lists the project management roles per ECE Senior Design project guidelines. Roles have been established but duties and responsibilities are flexible among the team to accomplish project goals.

Table 4: Team Organization

Team Member	Role
Peter Garate (EE)	Project Manager
Benjamin Martinez (CE)	Communications Manager
Emily Feller (CE)	Design Manager
Nicholas Byers (EE)	Test Manager
Ayana Rodgers (DASE)	Logistics Manager
Jacqueline Wrobel (EE)	Logistics Manager

The following roles and responsibilities have been agreed to amongst the initial 6-person team for all phases of development through May 2021, reiterating the flexibility of these roles and responsibilities for team effectiveness.

Peter - Project Manager

- Manages the development, implementation, and evaluation of complex designs. Oversees product construction and testing to ensure completion of the project as efficiently and effectively as possible. Evaluates and approves changes that impact scope, budget, or schedule.
- Responsible for
  - Architecture
  - Budget
  - Scheduling

Ben - Communications Manager

- Make sure the team communicates effectively/efficiently. Communicate with external advisors/stakeholders and schedule meetings.
- Responsible for:
  - Programming
  - Software/hardware integration

Ayana - Logistics Manager (1)

- Responsible for planning, coordinating, and monitoring inventory, transportation, and supply processes.
- Responsible for:
  - Data Analysis
  - Pre/Post Data Processing
  - Data Formatting

Jackie - Logistics Manager (2)

- Responsible for planning, coordinating, and monitoring inventory, transportation, and supply processes.

- Responsible for:
  - Optical/Sensor Hardware
  - Communications Systems
  - System Architecture

Emily - Design Manager

- Manage design tools, methods, and activities. Oversee development and assembly. Determine cost issues, producibility, quality, performance, reliability, serviceability, and intended lifespan.
- Responsible for:
  - Deep Learning
  - Machine Learning
  - Programming

Nick - Test Manager

- Manage the evaluation, recommendation and implementation of testing procedures and strategies for the project's systems, components, and/or modifications.
- Responsible for:
  - Mechanical
  - Electromechanical
  - 3D printing

Project Constraints

The constraints facing this project include movement, environment, expertise, and power supply. The constraints that pertain to movement are caused by our robot only having the upper-body half. This will limit the type of movement that the robot can make and imitate. The robot will be bound to mimic movements from the waist, neck, shoulders, arms, and head. Without the lower half, our robot will be restricted to being in one location at a time. The environment is limited to being indoors and the robot will always be on a tabletop.

The power supply constraints are caused by the Dynamixel motors and Raspberry Pi. The Dynamixel motors require a 12V power supply and the Raspberry Pi requires a 5V micro-USB power supply. These will both be connected to the robot and then will use a 120V power outlet.

The constraints facing this project as a team are due to overall expertise. The expertise that more specifically constricts our group is due to the lack of experience with machine learning and the robot itself. We will approach this by learning and researching on our own as well as relying heavily on teamwork to adjust to this learning curve.

To meet the high-level requirements of the social robotics project, being open-source and reproducible within resources at the University of Colorado at Colorado Springs, our group has decided to build our programs using Jupyter Notebook. Jupyter Notebook is an open-source web application that will allow our group to share live code, visualizations, and any explanatory text needed. This platform allows for easy future transitions should later teams pick up this project and continue. Additionally, another key high-level requirement is a software development plan that utilizes the strengths of the team's coding abilities and is familiar to the developers. To address this requirement, we have decided to use Python as our main coding language. This language is not only universal and versatile, but it is the team's strength in programming. Using Python hits both requirements because it is equally open-source, reproducible, and meets our best capabilities as developers.

Block Diagrams

Below illustrates the machine learning process as it is envisioned in the requirements phase.

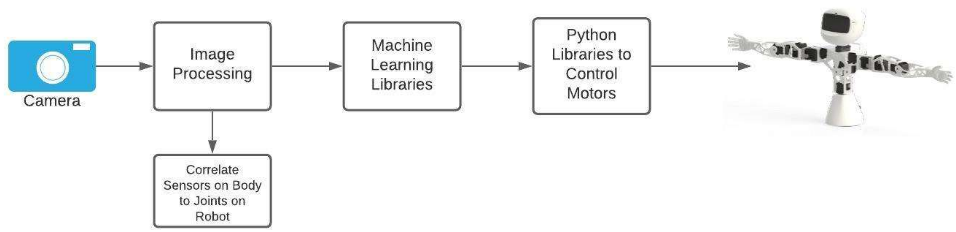

Figure 3: Machine Learning Block Diagram

Stretch Goals

As mentioned previously under section "Project Description", the robot will initially be stationary to a hard flat surface with basic human-like movements. Capability enhancements discussed with the customer include:

- Imitation of leg movement(s)
- Finger movement capability (effecters)
- Auditory and/or visual indicators

Budget

The initial budget discussed with the ECE department concluded that funds are available to construct a quality product using quality parts and material. The initial budget determination was established through the Bill of Materials (BOM) of similar existing projects. There is no cap on expenses at this time and the purchase of materials, parts, and software will be discussed with the customer on a case-by-case basis. The table below lists a very rough approximation of the BOM needed to meet this project's requirements. This BOM was derived from an existing Poppy Torso robot with additions of optical sensors hardware and 3D printing accessories and manufacturing consumables.

Table 5: BOM of Poppy Torso and Associated Hardware

Item	Quantity	Cost	Total
Raspberry Pi Board	1	34.12	34.12
microSD card (32GB)	1	18.00	18.00
OptiTrack Camera	1	NA	NA
Markers	10	20.00	200.00
Ethernet Cable	1	$8.99	$8.99
Dynamixel U2D2 (USB2AX)	2	$49.90	$99.80
USB Hub	1	$9.99	$9.99
Dynamixel MX-28AT (6pcs)	3	$1,529.50	$4588.50
Dynamixel MX-28AT (servo)	1	$239.90	$239.90
Dynamixel MX-64AT (servo)	4	$309.90	$1239.60

Dynamixel AX-12A (act)	2	$44.90	$89.80
HN07-N101 Horn & Bearing	19	$8.90	$169.10
HN07-I101 Horn & Bearing	12	$14.10	$169.20
HN05-I101	4	$15.40	$61.60
Cable (60 mm)	1	$10.90	$10.90
Cable (100 mm)	1	$11.90	$11.90
Cable (140 mm)	1	$12.90	$12.90
Cable (200 mm)	1	$14.40	$14.40
Filament (Glass Filled Nylon) Kg/2	1	$59.99	$59.99
Steel Nozzle	1	$9.99	$9.99
Glue Sticks	2	$1.00	$2.00
		Total:	$7050.68

Deliverables and Project Scheduling

The following section lists the projected schedule for team from the date of this published requirements document to May 2021. Tasks have been initially outlined based on current standing in development and their start/end dates for those tasks are listed below. Deliverables will be:

- Prototype
- Documentation
- Demonstration video(s)
- Power-Point presentation(s)

The following Phase Schedule is subject to change respective to each task. Deliverable dates will not and cannot change per customer request and requirement for this product.

Table 6: Projected Development Schedule

Phase 1: Project Scope & Requirements		
Task	**Start**	**End**
Task 1: Define Roles	10/23/20	10/30/20
Task 2: Decide Advisors	10/23/20	11/1/20
Task 3: Research Components	11/8/20	12/4/20
Task 4: Establish (Working) Budget	10/30/20	12/4/20
Task 5: Requirements Presentation	11/6/20	12/4/20
Phase 2: Preliminary Design Investigation		
Task 1: Research Components, Integration, etc.	12/18/20	1/29/21
Task 2: Setup Learning Algorithms	12/18/20	1/29/21
Task 3: Investigate Software Framework	12/18/20	1/29/21
Task 4: Simulation Runs	12/18/20	1/29/21
Task 5: Proposal Presentation	1/1/21	1/29/21

Phase 3: Fabrication & Modeling/Simulation		
Task 1: Print Robot	1/29/21	2/26/21
Task 2: Assemble Robot (Mechanical)	1/29/21	2/26/21
Task 3: Assemble Robot (Electrical)	1/29/21	2/26/21
Task 4: Simulate Joint Movements	1/29/21	2/26/21
Task 5: Design Review	1/29/21	2/26/21
Phase 4: Software & Hardware Integration		
Task 1: Integrate OptiTrack & Markers	2/26/21	4/30/21
Task 2: Process Data & Test	2/26/21	4/30/21
Task 3: Evaluate Data & Apply ML	2/26/21	4/30/21
Task 4: Optimize Software & ML	2/26/21	4/30/21
Task 5: Potentially Add Other Joints	2/26/21	4/30/21
Phase 5: Meeting Project Scope & Requirements		
Task 1: Enhancements	1/1/21	5/7/21
Task 2: Testing	1/1/21	5/7/21
Task 3: Deliverables	1/1/21	5/7/21
Task 4: Publish Documentation	1/1/21	5/7/21
Task 5: Final Presentation & Demonstration	1/1/21	5/7/21

Appendix

Section Work Cited

Project Background

- Shamsuddin, Syamimi, et al. "Humanoid Robot NAO Interacting with Autistic Children of Moderately Impaired Intelligence to Augment Communication Skills." *Procedia Engineering*, vol. 41, 2012, pp. 1533–1538.
- Yousif, Jabar, et al. "Evaluation Implementation of Humanoid Robot for Autistic Children: A Review." *International Journal of Computation and Applied Sciences*, vol. 6, Feb. 2019, pp. 412–120.

Standards

- https://collateral-library-production.s3.amazonaws.com/uploads/asset_file/attachment/17911/BNG-UL19-Robotics-WP-112219.pdf

Mechanical

- https://www.locarbftw.com/thinking-through-selecting-a-servo-for-the-rudder-control-system/
- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3134452/#:~:text=In%20the%20present%20study%2C%20healthy,rotation%20around%20the%20shoulder%20joint).
- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5260637/
- https://www.youtube.com/watch?v=lv-vgnHDV68
- https://www.robotis.us/mx-series/?_ga=2.85074523.338173415.1607905957-805268976.1604071436

Electrical

Optical

- https://www.nist.gov/news-events/news/2016/11/new-standard-helps-optical-trackers-follow-moving-objects-precisely
- https://www.researchgate.net/publication/279257786_Poppy_Humanoid_Platform_Experimental_Evaluation_of_the_Role_of_a_Bio-inspired_Thigh_Shape
- https://www.frontiersin.org/articles/10.3389/fnbot.2019.00065/full

Machine Learning

- https://www.sciencedirect.com/science/article/abs/pii/S1364661399013273
- https://www.frontiersin.org/articles/10.3389/frobt.2018.00001/full

Constraints

- *What Are Jupyter Notebooks? Why Would I Want to Use Them? Blended Learning in the Liberal Arts*, blendedlearning.blogs.brynmawr.edu/what-are-jupyter-notebooks-why-would-i-want-to-use-them/
- “Wiring Arrangement.” *Wiring Arrangement · Documentation of the Poppy Platform*, docs.poppy-project.org/en/assembly-guides/poppy-torso/wiring_arrangement.html.

Research Data

	ABS	PLA	PETG	Nylon	Carbon Fiber Fille	Polycarbonate	Polypropylene	PVA	Score criteria	
Ultimate Strength (Mpa)	40	65	53	40 - 85	45 - 48	72	32	78	3 points	
Stiffness	5 / 10	7.5 / 10	5 / 10	5 / 10	10 / 10	6 / 10	4 / 10	3 / 10	2 points	
Durability	8 / 10	4 / 10	8 / 10	10 / 10	3 / 10	10 / 10	9 / 10	7 / 10	1 point	
Maximum Service Temperature (°C)	98	52	73	80 - 95	52	121	100	75	Top 3 selected in each category	
Coefficient of Thermal Expansion (µm/m	90	68	60	95	57.5	69	150	85		
Density (g/cm3)	1.04	1.24	1.23	1.06 - 1.14	1.3	1.2	0.9	1.23		
Price (per kg)	\$10 - \$40	\$10 - \$40	\$20 - \$60	\$25 - \$65	\$30 - \$80	\$40 - \$75	\$60 - \$120	\$40 - \$110		
Printability	8 / 10	9 / 10	9 / 10	8 / 10	8 / 10	6 / 10	4 / 10	5 / 10		
Extruder Temperature (°C)	220 - 250	190 - 220	230 - 250	220 - 270	200 - 230	260 - 310	220 - 250	185 - 200		
Bed temperature (°C)	95 - 110	45 - 60	75 - 90	70 - 90	45 - 60	80 - 120	85 - 100	45 - 60		
Heated Bed	Required	Optional	Required	Required	Optional	Required	Required	Required		
Recommended Build Surfaces	Kapton Tape, ABS Slurry	Painter's Tape, Glue Stick, Glass Plate, PEI	Glue Stick, Painter's Tape	Glue Stick, PEI	Painter's Tape, Glue Stick, Glass Plate, PEI	PEI, Commercial Adhesive, Glue Stick	Packing Tape, Polypropylene Sheet	PEI, Painter's Tape		
Other Hardware Requirements	Heated Bed, Enclosure Recommended	Part Cooling Fan	Heated Bed, Part Cooling Fan	Heated Bed, Enclosure Recommended, May Require All Metal Hotend	Part Cooling Fan	Heated Bed, Enclosure Recommended, All Metal Hotend	Heated Bed, Enclosure Recommended, Part Cooling Fan	Heated Bed, Part Cooling Fan		
Flexible				X			X	X		
Impact Resistant	X			X		X				
Soft							X	X		
Composite					X					
Water Resistant			X				X			
Dissolvable								X		
Heat Resistant	X			X		X	X			
Chemically Resistant			X							
Fatigue Resistant			X	X		X	X	X		
Heated Bed Not Required		X			X					
Score (Arbitrary, based on project requireme	10	4	10	19	5	14	15	11		

https://www.simplify3d.com/support/materials-guide/properties-table/

Figure 4: 3D Printer Filament Data Research

<table>
<tr><td colspan="2">Brand</td><td colspan="2">TowerPro</td><td colspan="7">Herkulex</td><td colspan="7">Dynamixel</td><td colspan="3"></td></tr>
<tr><td colspan="2">Model</td><td colspan="2">MG996R</td><td>DRS-0101</td><td colspan="2">DRS-0201</td><td colspan="2">DRS0401</td><td colspan="2">DRS-0601</td><td>AX-12A</td><td colspan="3">MX-28T</td><td colspan="3">MX-64T</td><td colspan="3"></td></tr>
<tr><td colspan="2">Operating Voltage (V)</td><td>4.8</td><td>6</td><td>7.4</td><td>7.4</td><td>15</td><td>9.5</td><td>15</td><td>9.5</td><td>15</td><td>9 - 12</td><td>11.1</td><td>12</td><td>14.8</td><td>11</td><td>12</td><td>14.8</td><td colspan="3"></td></tr>
<tr><td colspan="2">Stall Torque (kg/cm)</td><td>9.4</td><td>11</td><td>12</td><td colspan="2">24</td><td>43</td><td>52</td><td>63</td><td>77</td><td>15.3</td><td>23.5</td><td>25.5</td><td>31.6</td><td>56</td><td>61</td><td>74</td><td colspan="3">Human Arm Motion</td></tr>
<tr><td colspan="2">Stall Current (A)</td><td></td><td>2.5</td><td></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td>1.5</td><td>1.3</td><td>1.4</td><td>1.7</td><td>3.9</td><td>4.1</td><td>5.2</td><td>Natural</td><td>Fast</td><td>Fastest</td></tr>
<tr><td rowspan="2">No Load speed</td><td>(RPM)</td><td>59</td><td>71</td><td>60</td><td colspan="2">68</td><td colspan="2">62</td><td colspan="2">61</td><td>59</td><td>50</td><td>55</td><td>67</td><td>58</td><td>63</td><td>78</td><td>12</td><td>18</td><td>477</td></tr>
<tr><td>(sec/60°)</td><td>0.17</td><td>0.14</td><td>0.166</td><td colspan="2">0.147</td><td colspan="2">0.162</td><td colspan="2">0.164</td><td>0.169</td><td>0.2</td><td>0.182</td><td>0.149</td><td>0.172</td><td>0.159</td><td>0.128</td><td>0.853</td><td>0.56</td><td>0.021</td></tr>
<tr><td colspan="2">Weight (g)</td><td colspan="2">55</td><td>45</td><td colspan="2">60</td><td colspan="2">123</td><td colspan="2">145</td><td>54.6</td><td colspan="3">72</td><td colspan="3">126</td><td colspan="3"></td></tr>
<tr><td colspan="2">Dimensions (mm)</td><td colspan="2">40.7x19.7x42.9</td><td>45x24x32</td><td colspan="2">45x24x32</td><td colspan="2">56x35x38</td><td colspan="2">35x56x38</td><td>32x50x40</td><td colspan="3">35.6x50.6x35.5</td><td colspan="3">40.2x61.1x41</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Resolution</td><td>(deg)</td><td colspan="2"></td><td colspan="3">0.325</td><td colspan="4">0.163</td><td>0.29</td><td colspan="6">0.088</td><td colspan="3"></td></tr>
<tr><td>(steps)</td><td colspan="2"></td><td colspan="3">1024</td><td colspan="4">2048</td><td>1024</td><td colspan="6">4096</td><td colspan="3"></td></tr>
<tr><td colspan="2">Gear Reduction Ratio</td><td colspan="2"></td><td>1/266</td><td colspan="2">1/266</td><td colspan="2">1/202</td><td colspan="2">1/202</td><td>1/254</td><td colspan="3">1/193</td><td colspan="3">1/200</td><td colspan="3"></td></tr>
<tr><td colspan="2">Operating Angle (deg)</td><td colspan="2">360</td><td colspan="7">320, continuous</td><td>300, continuous</td><td colspan="6">360, continuous</td><td colspan="3"></td></tr>
<tr><td colspan="2">Max Current (mA)</td><td colspan="2"></td><td></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td>900</td><td colspan="3">1400</td><td colspan="3">4100</td><td colspan="3"></td></tr>
<tr><td colspan="2">Standby Current (mA)</td><td colspan="2"></td><td>450</td><td>670</td><td></td><td></td><td>30</td><td></td><td>30</td><td>50</td><td colspan="3">100</td><td colspan="3">100</td><td colspan="3"></td></tr>
<tr><td colspan="2">Temperature Range (C°)</td><td colspan="2">0 - 55</td><td>0 - 85</td><td colspan="2">0 - 85</td><td colspan="2">0 - 80</td><td colspan="2">0 - 80</td><td>-5 - 85</td><td colspan="3">-5 - 85</td><td colspan="3">-5 - 80</td><td colspan="3"></td></tr>
<tr><td colspan="2">Protocol</td><td colspan="2"></td><td colspan="7">TTL Full Duplex Asynchronous Serial</td><td colspan="7">TTL Half Duplex Asyncronous Serial / RS-485</td><td colspan="3"></td></tr>
<tr><td colspan="2">Module Limit (addresses)</td><td colspan="2"></td><td>254</td><td colspan="2">254</td><td colspan="2">254</td><td colspan="2">254</td><td>254</td><td colspan="3">254</td><td colspan="3">254</td><td colspan="3"></td></tr>
<tr><td colspan="2">Communication Speed (Mbps)</td><td colspan="2"></td><td>0.67</td><td colspan="2">0.67</td><td colspan="2">1</td><td colspan="2">1</td><td>0.007343 - 1</td><td colspan="3">0.8 - 3</td><td colspan="3">0.8 - 3</td><td colspan="3"></td></tr>
<tr><td rowspan="5">Feedback</td><td>Position</td><td colspan="2"></td><td>Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td>Yes</td><td colspan="3">Yes</td><td colspan="3">Yes</td><td colspan="3"></td></tr>
<tr><td>Temperature</td><td colspan="2"></td><td>Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td>Yes</td><td colspan="3">Yes</td><td colspan="3">Yes</td><td colspan="3"></td></tr>
<tr><td>Load Voltage</td><td colspan="2"></td><td>Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td>Yes</td><td colspan="3">Yes</td><td colspan="3">Yes</td><td colspan="3"></td></tr>
<tr><td>Input Voltage</td><td colspan="2"></td><td>Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td>Yes</td><td colspan="3">Yes</td><td colspan="3">Yes</td><td colspan="3"></td></tr>
<tr><td>Compliance/PID</td><td colspan="2"></td><td>Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td>Yes</td><td colspan="3">Yes</td><td colspan="3">Yes</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Material</td><td>Gears</td><td colspan="2" rowspan="2">Aluminum 6061-Plastic</td><td>Plastic</td><td colspan="2">Metal</td><td colspan="2">Metal</td><td colspan="2">Metal</td><td>Plastic</td><td colspan="3">Metal</td><td colspan="3">Metal</td><td colspan="3"></td></tr>
<tr><td>Body</td><td>Plastic</td><td colspan="2">Plastic</td><td colspan="2">Plastic</td><td colspan="2">Plastic</td><td>Plastic</td><td colspan="3">Plastic</td><td colspan="3">Plastic</td><td colspan="3"></td></tr>
<tr><td colspan="2">Motor</td><td colspan="2"></td><td>Cored</td><td colspan="2">Coreless</td><td colspan="4">FAULHABER Coreless</td><td>Cored</td><td colspan="6">Maxon RE-MAX</td><td colspan="3"></td></tr>
<tr><td colspan="2">Position Sensor</td><td colspan="2"></td><td colspan="7">Potentiometer</td><td>Potentiometer</td><td colspan="6">Contactless Absolute Encoder</td><td colspan="3"></td></tr>
<tr><td colspan="2">Daisy Chain Communication</td><td colspan="2">No</td><td colspan="7">Yes</td><td colspan="7">Yes</td><td colspan="3"></td></tr>
<tr><td colspan="2">Dead Band Width (us)</td><td colspan="2">1</td><td></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td></td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="2">Plug Type</td><td colspan="2">JR (Fubata)</td><td></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td></td><td colspan="3"></td><td colspan="3"></td><td colspan="3"></td></tr>
</table>

Figure 5: Servo Data Research