Embodied Intelligence: The embodiment of Bio-Inspired Physical Intelligence and its Realization in Real World Robotic Applications Demonstrated with A Conceptual Implementation

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“Learn from nature: that is where our future lies”

—Leonardo Da Vinci

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Moreover, I would like to thank to Dr. Alexandar Klimchik for this supervision over this project and providing his valuable insights on the domain of concern. His idea, thoughts and expertise made this project possible.

This project lies relatively close the domain Bionic or body augmentation (as Prof.Simon described it in our very first interaction) a sub-topic, which I aspired to explore at the beginning of my Master's journey and as my studies concludes i have been able to explore the topic with an attempt to contribute to this field. I am happy.

Abstract

The project focuses on the study of an embodied physical intelligence paradigm in the real world with a focus on integration in new robotic components. Particular attention will be paid to the realization and function of the entire sense-think-act robotic paradigm in biological systems. The project focuses on physical intelligence, to study reactions and actions in different interaction scenarios, energy efficiency, and memory principles. We will further look at the potential electro-mechanical realizations of the observed principles. This thesis work purposes a bioinspired robotic tail as a paradigm in general, to control maneuverability and its potential realizations on the software and hardware levels, motions primitives realized in nature for specific behaviours and their potential transfer to robotic components.

The in-depth analysis of physical intelligence in biological systems. The focus is on realization of the function of bio-inspired gyroscope, the animal tail observed in biological agents and embedding them in new robotic components. The study incorporates the phenomenon of action and reaction in different scenarios. And making them energy efficient while understanding the memory principles governing them. This will alter the traditional practices currently being implemented to interact with the environment. The tails of animals play crucial roles in enhancing their physical abilities, particularly in quadrupeds. Agents with physical intelligence are created for specialized tasks while computational intelligence can be considered to be general purposed. When deployed in very harsh environment the agents require to be more physically intelligent as under such condition computational intelligence cannot be relied upon, thus highlighting the importance of environment specific utilities for such agents. For instance, cheetahs use their tails to change direction during high-speed chases, allowing them to catch prey more effectively. The working principle of an inertial adjustment mechanism is to align the Center of Mass by generating forces at the point it is attached to the main body. There are four categories of IMU correction methodologies practiced in engineering, the concept of the tail is the most observed in nature.   My thesis work purposes a bioinspired robotic tail as a paradigm in general, to control maneuverability and its potential realizations on the software and hardware levels, motions primitives realized in nature for specific behaviors and their potential transfer to robotic components. The aim is to study the iterations of an agent equipped with a mechanical tail in different gait motion based inside a sim-world. The focus will be on creating a set of paradigms for an ideal bio-inspired tail design.

- Replicate a tail for mechanical systems, in simulation environments.
- Observe the gait motion under different situations and compare it with the original gait practiced by the agent.
- Improvise on the learning methods used to teach the agent.

- Scaled on the software level as well as hardware level in pursuit of transferring them to robotic components.
- Understand or more precisely fabrication of the method for real-world implementation.
- Bring them closer to the intellectual capability equal to biological organisms or even surpass those in some cases.

The inertial control system discussed in this report can be utilized for rehabilitation of people with temporary or permanent walking disability like for athletes or accident survivors with movement disability. Some individuals may suffer from Acute or Chronical Vestibular disorder. They may suffer from vertigo or walking disorder. Such individuals can benefit from the concept of mechanical tail to correct their gait.

Keywords: Embodied Intelligence, Physical Intelligence, Bio-inspired Tail.

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Chapter 1

Introduction

Human fascination with building mechanical systems inspired from nature, dates to as far as recorded history can be observed. Great inventors from the past had taken into consideration the instances of intricate engineering practiced by nature. The likes of inventors such as Heron of Alexandria (Papadopoulos, 2007) well-known for introducing biomimicry in his inventions where he creates a toy puppet that mimics the gait motion of a bird. Similarly, Leonardo Da Vinci a renowned personality from the past whose inventions and work are studied today as well to gain inspiration, invented a menagerie of mechanical devices. His fascination with the flight of birds made him design many flights capable machines, one of which is the Ornithopter (Gurney, 2020), an aircraft replicating the flapping motion of birds and flying insects. Similar and more renowned were the achievements of the Wright brothers credited with the invention of the first airplane.

The inspiration from nature is not only limited to mimicking gait but also capturing other aspects of nature like the structure of honeycomb taken from bee-hive to introduce structural integrity to architectural marvels. Also, George De Mestral invented the ‘velcro’ used in textile industries. It was inspired by burs found on plants. And there as many more examples of technologies that have inspired researchers towards innovation from the instances of nature. These inspirations have been fostering advancement in multiple sub-fields of science and technology for hundreds if not thousands of years.

My work, the submission for the master's thesis, is an attempt to understand the past, present and future of this subject. With the understanding of the advancements made on the topic and the new research paradigms being established, this is an attempt to appraise the previous work as well as introduce a new and better approach to solve problems in the domain of this subject.

In this section, embodied intelligence (E.I) will be discussed by elaborating the topic and expressing the underlying nuances of this field and use case in real-world. And practices that have been used to solve the task. The section will be concluded by defining the aim and objective of this study. The focus will be on highlighting the importance of ‘Physical Intelligence’ in artificial systems and the realization of the deciphered technique in real application and building a sustainable solution.

At what some consider to be the peak in the evolution cycle for the species homo-sapiens(Latin for the phrase wise being), technology has progressed exponentially to a state where the next step in the progress is to achieve an entity that can surpass the very capabilities that has helped this species to become dominate on the planet. After thousands of years of evolution, sapiens have evolved into a being that can translate, if not all but a major portion of the knowledge that it has acquired in its evolution cycle to an artificially created computational device. This makes the device capable of thinking and reasoning in the same way as its creators. This technology has been coined by the term artificial intelligence (A.I). As explained in (Floreano and Mattiussi, 2008), this technology uses Artificial Neural Networks (ANN), the concept itself is inspired by biological nervous systems. In recent years, this subject has seen unprecedented development due to the collective efforts of researchers working in different domains of technology. A.I enabled systems are capable of sensing and interpreting their surroundings and performing logical reasoning to better understand the state of task assigned to them. This is similar to decision making capability of sapiens. Conventional A.I paradigms are used for predictive modelling where they learn from a set of information and constraints provided by a human teacher. This allows its creators to adhere to solutions for complex tasks much quicker than any average sapient being can perform. Later in this section a major sub-topic of A.I which is very crucial to encompass the core objectives of this thesis will be discussed. This sub-topic is called Reinforcement Learning which will be discussed in section 1.3

In parallel to this advancement, the field of robotics has seen ground-breaking development in recent years. Almost 50 years ago the first robots were deployed in industries to automate the repetitive factory processes. Making the industries more efficient in meeting the ever-growing demand. These robots were first semi-automated, and with progress over the years have achieved full-scale automation. They have become successful in achieving proficiency in tasks across different domains. The robots of the present day are not just limited to industries, they have entered our homes, they are being included in our daily life, with applications in multi-domain operations.

Thus, the ever-curious species of homo-sapiens have pondered upon the new objective to amalgamate both A.I and robotics. This is to build an agent that can co-work and co-exist with sapiens and venture on exploring new frontiers.

1.1What is Embodied Intelligence?

This brings us to the core discussion of this research work called 'Embodied Intelligence'. The term itself is dubious, and researchers have debated on how to exactly define the subject. The term has seen its roots in the domain of philosophy and psychology, where it has been described as the cognitive capability of any entity. Here, the physiology of the agent is not taken into account. But in their work, the authors of (Lawrence and Shannon, 2024) state by emphasizing the significance of an agent's physical body towards their cognitive abilities. Further unifying researcher to address the topic as study of the body or the body's interactions with the environment and how it constitutes or contributes to cognition in ways that require a new framework for its investigation. The term is encompassed in the domain of technology by (Cangelosi et al, 2015) defining it as an approach to design and understand intelligent behavior in agents considering the relation between the agents and their environment governed by the agent’s body.

In (Floreano and Mattiussi, 2008) the authors describe behavior of an agent as an embodiment of intelligence. They describe behavior as a sequence of interactions between an organism and its environment, where the action of an agent can change the way, they preserve their environment and therefore may alter its future actions. Further in their work they define the aspects of such a system, constituent of a body with sensory and motor coordination making it capable to interact with its environment while possess a computational system able to map sensory stimulation onto motor action. This paradigm highlights the major components that will address the advancement to develop an agent possessing intelligence.

The subject is the integration of robotics and A.I which enables smart agents to engage with their environment, like living beings. This field may utilize concepts from nature to create robots that can use sensory data to interpret their immediate surroundings and with motor control, perform maneuvers like animals, insects, or humans. These robots must be sophisticated to learn and adapt as living beings. Implementation of RL, imitation learning, or other machine learning techniques will help these smart agents to learn from their experience and adapt to new situations.

As interpreted from the work of (Cangelosi et al, 2015) where the authors have defined the advancement in the fields of Embodied Intelligence linked to development taking place in three different domains of technology which are discussed below.

Morphological Computing: This field concerns the body plan of an agent. The body plan refers to the anatomy of the agent. In (Cangelosi et al, 2015) the author states that a body plan enables an agent to exploit interactions with its environment and thus perform computations. In (Mintchev and Floerano, 2016) morphology has been defined as vital for building behavioral and locomotion strategies for artificial systems, morphological improvement can improve dynamic performances by reducing tradeoffs during locomotion while introducing new functionalities. The topic has been elaborated on in (Pfeifer et al., 2007) where the authors state that it is not limited to anatomy of the agent but also concerns with the kind of sensors and on the agent's body and where are they found. This introduces dexterity, stability and efficiency to a system.

Embodied Cognition: The field deals with introducing cognitive capability into an agent. These capabilities can range as individual or in pairs of the sensory information that can be observed and transmitted. Perception is a major sensory attribute that embeds intelligence in agents. As per (Pfeifer et al., 2007) this enables an of processes as abstract as problem solving, memory, attention and language. In (Cangelosi et al, 2015) the importance of higher order cognitive capabilities has been discussed the ability of object categorization and representation, language learning and processing, and even the acquisition of abstract concepts such as numbers, which enables an agent to engage with its environment.

Sensory-Motor Co-ordination: In this field the focus is on deciphering a control system or policy that will bridge the gap between the sensory stimulus received and proceed with any corresponding action required to be performed at any given state in time. In (Cangelosi et al, 2015) the importance of sensory motor coordination is discussed where they highlight that key function observed here is enabling an agent to gather information, to make an action plan and reduce complexity of task.

This thesis work will focus on improving the functionality of body plan by introducing physical intelligence to the system thus establishing a trade-off for computational resources and reducing the work exerted on the sensory–motor system. The next section discusses and elaborates on the topic of physical intelligence as a paradigm to upscale the performance of an agent.

1.2 Physical Intelligence

For many years it has been considered that Intelligence is an attribute that is only achievable by the neural structures of sapiens. The scientific community has long debated this and has discovered instances of intelligence across all species on the planet. They studied how these instances have propagated along the evolutionary cycle of any given species. This has provided valuable insights about cognition, how it is practiced and how it is embedded in the sensory-motor model of a being (Sitti, 2021).

This development has enabled new frontiers of research in robotics and A.I in domains as discussed in the previous section. There is a concept so subliminal but a key part of the model of intelligence that it is often ignored. This concept is encoded in the body of an agent, known as Physical Intelligence. This section has a brief discussion on this topic. As expressed by the author in (Sitti, 2021) the major challenges in developing or encompassing the full strength of AI are related to the need of combine algorithmic (brain) and physical (body) capabilities.

In their work the authors of (Pfeifer et al., 2007) write about intrinsic dynamics. They argue that the brain has partial control over the body, magnifying the effects of physical phenomenon on the body and the ability of the body to learn and adapt to them. They refer to dynamics embodied within a physical system; these intrinsic dynamics are considered to be natural to the physical system, thus highlighting that they can be learned easily and further stating to the utilization in the domain of robotics systems. This intrinsic dynamic is the intelligence housed in the body of agents, and in this work, it will be referred to as physical intelligence (PI) as done in (Sitti, 2021).

In his work the author of (Sitti, 2021) writes about intelligence not being limited within the brain of human-made machine and biological organisms but is also encoded in the body. They define PI as physically encoding of the capabilities of sensing, actuation, control, memory, logic, computation, adaptation, learning and decision-making into the body of an agent.

The evolutionary cycle as discussed in (Sitti, 2021 and Siciliano and Khatib, 2008 1423-1451) the evolution of any species involves the development of Neural Itelligence (counterpart of computer intelligence) and Physical intelligence. This makes that species capable of adapting to its environment by generating its own control system and body configuration over this cycle. Thus, by the creation of an artificial being capable of enhanced PI capabilities, it would proceed towards a future where this agent can actively adapt to their physical environment without any human intervention. They will be able to survive in resource constraint physical environment. The authors of both works mentioned here have argued that an inspiration from biological organisms is an effective manner to introduce PI. As, over eons of evolution the organisms that inhabit the planet earth have prevailed to thrive in what could have once been an inhospitable environment for them.

The subject is so undermined that even the well-established researchers have doubts on how to provide a definition for the topic that will justify it and the practices that take place in this domain. Thus in (Miriyev and Kovač, 2020) the authors set out to highlight that PI will redefine Human-Robot interaction (HRI) and create a human-robot ecosystem. But there are obstacles in establishing an efficient community, which lack multidisciplinary skills for the creation of PI, thus proposing a framework and encouraging for educating the researchers to gain skills for the creation of PI.

Agents with physical intelligence are created for specialized tasks while computational intelligence can be considered to be general purposed. As expired by the author in (Sitti, 2021) as when deployed in very harsh environment require the agents to be more physical intelligent as under such condition computational intelligence cannot be relied upon, thus highlighting the importance of environment specific utilities for such agents.

There are many methods in which physical intelligence can be introduced to artificial systems. These methods, as discussed previously, are practiced depending on the environmentally specific constraint in which the agents must be deployed. As discussed in (Sitti, 2021), encoding various advanced physical capabilities and properties in the agent body, such as mechanical logic operations, memory, computation and decision making, reconfigurability, modularity, physical (re)programmability, smart structuring (e.g., multiscale structures, metamaterials, origami, kirigami, tensegrity), hierarchical multi-length scale structuring, smart mechanisms, taxis behaviour, and collective and emergent behaviour. Such capabilities would require minimal or no CI.

Materials and structures can be designed to enable self-adaptive, self-regulatory, self-degrading, self-cleaning, and other autonomous behaviours. Morphology can be designed in specific ways to enable energy-efficient, sustainable, robust, easy-to-control, safe and self-adaptive behaviours. Tensegrity structures, which occupy a constant volume in space through the use of discontinuous compressive devices like pistons when connected with network of cables, can enable extremely lightweight yet strong mechanical structures for agent bodies. Memory is an essential system component to enable CI and self-adaptive PI behaviour by introducing temporary/permanent plastic deformation (e.g., memory foams, viscoelastic soft elastomers), the ability of the material to retain shape can enable volatile or non-volatile memorization of the mechanical deformations. Multiple (team) or a large number (swarm) of homogeneous or heterogeneous agents can collectively behave to enhance their intelligence, functionality, robustness, fault tolerance and complex behaviours beyond the limits of the individual agents.

1.3 Robot Learning

Learning is an essential tool used by living organisms that interact with their environment. It provides the organism with information about the action-reaction that takes place in the environment as they interact with it. The learning methods have also evolved over the evolutionary cycle of living organisms. Thus, these methods have been incorporated in the domain of robotics to make self-sufficient robots. In their work (Siciliano and Khatib, 2008, 1395-1422) the authors speak about different bio-inspired learning mechanisms like associative, reinforcement, or imitation learning in robotic applications. From their work it is understood that associative learning mechanisms enable map-building, localization, and navigation capacities in robots, as such instances have been studied in sapiens where the head direction cell in the hippocampal of the brain, Similarly reinforcement learning is inspired by the function of dopaminergic neurons, a reward mechanism similar to the brain of sapiens (Siciliano and Khatib, 2008, 1395-1422). Similarly imitation learning is learning from human demonstrations.

From the prospect of this study reinforcement learning is an ideal approach to make A.I enabled agents learn and adapt to the environment and surroundings. Later in this work, a few domains specific methods considered for implementing reinforcement learning have been discussed.

Reinforcement learning is the ability by which artificial agents can map state to actions in order to get a numerical reward. They are closed-loop problems because the learning system’s actions influence its later inputs. The formulation is intended to include just these three aspects—sensation, action, and goal (Sutton and Barto, 20018).

1.4 Real World Prospect of Bio-Inspired Embodied Intelligence

These agents can be deployed in multiple domains as mentioned below but are not limited to those. Living beings will allow the robot to traverse difficult terrain.

Industrial Robots: Embodied Intelligence can be utilized to create smart robots that can perform complex tasks in industries. Modification in the overall structure to introduce more dexterity and structural equilibrium inspired from nature will make these robots more efficient. For example, the tusk of elephants can lift heavy loads of all shapes and sizes and precisely engineered locomotive wheels or legs like those of living beings will allow the robot to traverse difficult terrain.

Autonomous Systems: There are unmanned vehicles equipped with arrays of sensory devices, which navigate both on land and air. These vehicles are utilized for transporting goods, for daily commute by humans, and terrain exploration and surveillance. Underwater unmanned vehicles have evolved in recent years but still hold propulsion techniques from the past. Introducing intelligence within those vehicles using A.I and biomimicry will make them more agile in the unexplored underwater environment. And advanced perception will provide data gathering and interpretation skills just like humans.

Service Robots: The purpose of these robots is to assist humans within their household environment or any other indoor/outdoor environment. They can be considered as caregivers/assistants. These robots are supposed to, but necessarily look like humans and have cognitive and physical capabilities at par with humans to co-work with them in the real world. Such are the kind of robots that are known as humanoids. Extensive research in body planning and cognitive capabilities will make them blend well in the real world.

Healthcare Robots: The purpose of these robots is to assist humans within their household environment or any other indoor/outdoor environment. They can be rescuers may have to endanger their lives. With physical intelligence these robots will become more aware of their surroundings and can perform difficult tasks which may even be life-threatening for humans.

1.5 Scope of the project

Robots are housed with in-built IMU and Gyroscopes that help them to maintain stability and orientations while walking, jumping or running. These conventional methods, though fulfil their task, are still not able to achieve swift maneuvrability through tight space and are unable to make sharp turns. Thus, this may lead to damage endured by the robots and also to the environment in which it has been deployed. Moreover, to maintain stability, they are not able to achieve high speed for demanding tasks.

Over the year researchers have looked for effective methods to make robots more agile in demanding environments. Recently, many works has been done to introduce a tail to these mechanical bodies with an artificial tail. This has been adopted from animals that are known to utilize tails for inertial adjustment like cats, kangaroos and chetahs. The authors of (Saab et al., 2018) in their work state that while tails are the most obvious inertial adjustment mechanism used by animals, any motion of an appendage or body mass can be used for reorientation such as wings, spines or legs. By observing these functionalities scaled over a wide range of sizes and uses, engineers have been inspired to apply inertial adjustment mechanisms to mobile robotics to further enhance stabilization and manoeuvrability of these systems.

The tails of animals play crucial roles in enhancing their physical abilities, particularly in quadrupeds. For instance, cheetahs use their tails to change direction during high-speed chases, allowing them to catch prey more effectively. Additionally, squirrels and lizards utilize their tails to adjust body orientation in mid-air, ensuring safe landings. Tails are also essential for balancing, swimming, hopping, courtship, and defense. These versatile tails have garnered the attention of robotic engineers and have been established as solutions for addressing various challenges in the field of robotics.

The instances of tail being used as inertial control system in not limited to animals on land, but it can also be seen in marine organisms as discussed in (Omari et al., 2022). Here the authors speak about how the tail help marine animals achieve great steering capabilities in underwater conditions where drag forces and pressure are higher than usual. The sea creatures have remarkable capabilities to steer and make difficult maneuverer that any other creature on the planet is incapable to perform. These creatures have excelled the art of underwater motion with over years of evolution. There are many marine creatures which have inspired research to introduce features in robots like manipulators inspired from octopus and seahorses and morphologies of drones inspired from fishes have made more dexterous.

The working principle of an inertial adjustment mechanism is to align the Center of Mass by generating forces at the point it is attached to the main body (Saab et al., 2018). As they describe that there four categories of IMU correction methodologies practiced in engineering, the concept of the tail is the most observed in nature.

The work of (Saab et al., 2018) highlighted that for mechanical design, the majority of research has focused primarily on single-body planar pendulums and covers a wide range of masses and lengths. Defining different approaches to achieve a ideal tail configuration.

- Planar tails operate in a single-degree of freedom (DOF) either in the pitch, yaw or roll-direction. Planar tails provide enhanced performance about a single-body-axis with the advantage of simpler design and implementation

- Spatial pendulum like tails is two-DOF mechanisms that operate in a combination of planes by utilizing active pitch and yaw DOFs. Spatial tails greatly increase workspace and provide multi-axis enhanced performance capabilities but require increased actuator unit design complexity and control.

- Articulated tails utilize two or more active DOFs to enable spatial capabilities.

- The continuum tails closely emulate the natural motions and functionalities of biological tails and utilize various forms of actuation such as cable systems, pneumatic pressure and mechanical layer jamming

This work will try to study the iteration of an agent equipped with a mechanical tail in different gait motion based inside a sim-world. The focus will be on creating a set of paradigms for an ideal bio-inspired tail design.

1.6 Aim and Objectives

1.6.1 Aim

The in-depth analysis of physical intelligence in biological systems. The focus will be on realization of the function of bio-inspired gyroscope, the animal tail observed in biological agents and embedding them in new robotic components.

The study will incorporate the phenomenon of action and reaction in different scenarios. And making them energy efficient while understanding the memory principles governing them. This will alter the traditional practices currently being implemented to interact with the environment.

1.6.2 Objective

- Replicate a tail for mechanical systems, in simulation environments.
- Observe the gait motion under different situations and compare it with the original gait practiced by the agent.
- Improvise on the learning methods used to teach the agent.
- Scaled on the software level as well as hardware level in pursuit of transferring them to robotic components.
- Understand or more precisely fabrication of the method for real-world implementation.
- Bring them closer to the intellectual capability equal to biological organisms or even surpass those in some cases.

Chapter 2

Literature Review

This section highlights similar work being practiced in the domain of bio-inspired robotic tail as gyroscope for self-balancing robotic agents.

2.1 Proprioception and Tail Control for Quadruped Robots

In their work the author of (Yang et al., 2023) present proprioception as an option for adapting to unstructured terrain proposing a strategy that incorporates perception, control, and tails to synergistically improve extreme terrain traversal. They emphasize the optimization of the proposed nonlinear model predictive controller (NMPC) that governs the maneuverability of the tail structure. Thus, providing a method where the tail is particularly effective at maintaining stability when encountering a terrain change

2.2 Safe Landing of Falling Quadruped Robots Using Tail

Another interesting work presented by (Tang et al., 2023) where the authors have investigated the aerial reorientation and stable landing as observed in many feline animals. They used a Mini chetah bot equipped with a 3-dof tail to prevent disturbance along pitch, yaw, roll directions. Utilizing a joint actuator to trajectory optimization-based controller for the flight phase and a compliant joint PD controller for the stance phase. Thus, presenting a simple and effective control framework to demonstrate the feasibility of system integration.

2.3 Steering with an Active Tail

In (Casarez and Fearing, 2018) the authors have created LoadRoACH, a 55 g palm-sized legged robot, is developed to carry the active tail payload used in turning experiments. A steady-state turning model predicts the achievable turn speed of the robot on carpet, and open-loop turning experiments characterize the performance of the two-tail contact turning strategies. Tail drag turning provides comparable turning maneuverability to differential drive turning gaits on carpet and gravel surfaces.

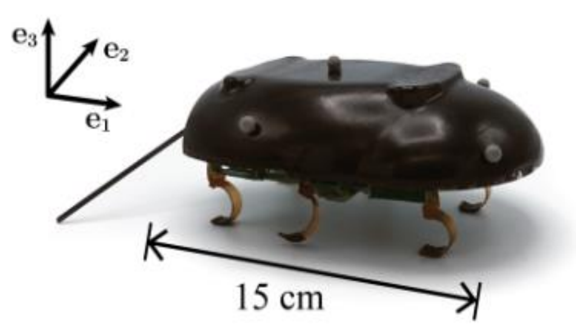

Fig.1. LoadRoach (Casarez and Fearing, 2018)

2.4 Manipulator as a Tail

By far the most innovative idea from all the literature that I have read has been proposed by (Yang and Hwangbo, 2024) here the authors purpose to use a 6-DoF manipulator mounted a mini cheetah bot as an effective tail for learning rapid turn, aerial reorientation and balancing. Further highlighting the multi-purpose use of the manipulator. The authors have created a sim world representation and trained a robotic agent using a Reinforcement learning algorithm.

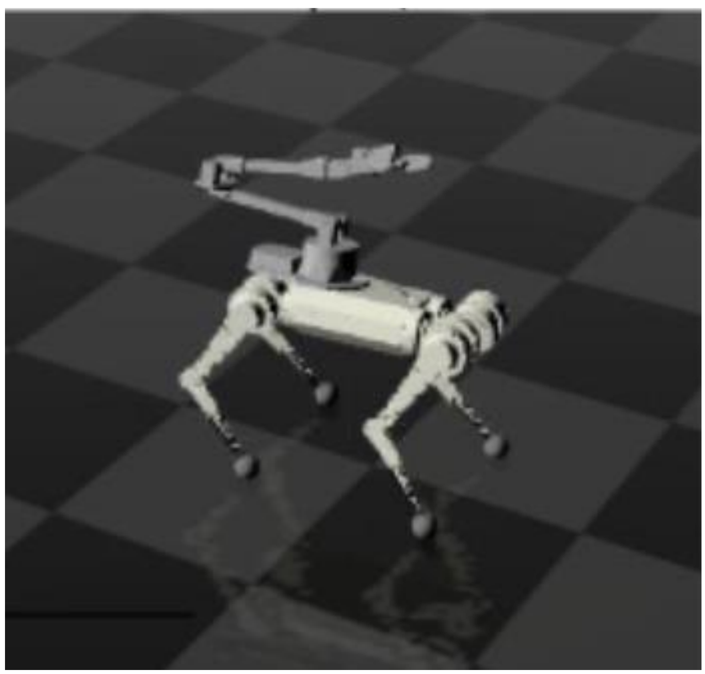

Fig.2. A quadruped robot, Mini Cheetah, equipped with a WidowX250S 6-DoF manipulator (Yang and Hwangbo, 2024)

Thus, with groundbreaking results the author proposes a manipulator on a quadruped robot as an effective substitute for a mechanical tail with effective results for high velocity applications. Thus, it indicates that the manipulator can improve the agility and stability of the quadruped robot. Though the experiment took place in a sim-world the degree of improvement in the gait motion and the innovative concept of utilizing a manipulator as a tail can revolutionize the industries with potential application for future studies.

2.5 Manipulator for Dynamic Stability:

In their work the authors of (Huang et al., 2024) have described the use of a manipulator attached to a quadruped as an augmented mechanical tail. This work shows how a manipulator can be an asset for legged locomotion at high speeds or under external perturbations, where the arm serves beyond manipulation. Since the system has 15 degrees of freedom (twelve for the legged robot and three for the arm), off-the-shelf reinforcement learning (RL) algorithms struggle to learn effective locomotion policies. Inspired by Bernstein's neurophysiological theory of animal motor learning, we develop an incremental training procedure that initially freezes some degrees of freedom and gradually releases them, using behaviour cloning (BC) from an early learning procedure to guide optimization in later learning.

Chapter 3

Methodology

The Project has been implemented in simulation environment and later a proposal has been shared on how to realize the supposed paradigm in real world applications. This section has a brief layout of how the experiment has been implemented in the simulation environment the practiced used to achieve the task at hand.

3.1 Simulation

For the implementation of this task the following simulation software had been considered

- CoppeliaSimEDU
- MuJoCo
- Issac-Sim

An attempt was made to practice the principle in all the above-mentioned simulation environments. Each of the simulation environment had its own pros and cons. For the final implementation MuJoCo was used with consideration of the scope of this project. It is one of the most versatile simulation software that supports seven different languages and five different programming approaches. With many APi available for smooth working of the project and easy to use interface. It was the best choice to work with as it supports five different Physics Engines.

3.1.1 CoppeliaSimEDU

Fig.3. Coppelia Sim (CoppeliaSim, 2024)

This is a good tool that has been used by some of the best research institute in the world. The tool is compatible with 6 different languages and has an interactive GUI. With ease to implement API’s and active development to make the tool better it is a good choice to implement the scheme of this project. One of the major drawbacks with this tool was a framework for reinforcement learning. There are very few works on reinforcement learning being implemented on this software and that require of building root packages that will act as an emulator for the Gymnasium package that we hold to use with this work. Initial attempt to test were done on this tool but later a switch was made for quick development of this work.

3.1.2 Issac Sim

Fig.4. Isaac Sim (Nvidia Corporation, 2024)

Isaac Sim is a software platform built to support the increasingly roboticized and automated world simulation environment which runs both the simulation and training on the GPU and is capable of simulating thousands of robots in parallel (Rudin et al,2022). The tool is currently considered the best in the industry, but the biggest drawbacks are the computational resources required to successfully run the software on native systems.

The tool was considered for the implementation but due to a resource constraint device the idea to work with this tool was dropped. But if in the future a device capable to support this exceptional tool is acquired then the currently saucerful task be carried out in the Isaac Sim software provided by Nvidia as a part of the Omniverse development suite.

3.2 Anaconda Package Manager

Anaconda is a distribution of the Python and R programming languages for scientific computing (data science, machine learning applications, large-scale data processing, predictive analytics, etc.), that aims to simplify package management and deployment. The distribution includes packages suitable for Windows. Virtual environment can be created with suitable package to address this solution implementation for this project.

ANACONDA.NAVIGATOR

Fig.5. Anaconda Software Manager (Anaconda Inc, 2024)

- Download the installer from the following link https://docs.anaconda.com/anaconda/install/windows/

- Install the software at the default recommended location

- Open Command prompt and type, conda activate

- To create a new package type conda create –n NAME OF YOUR CHOICE python==3.8.19(the project has been tested on python version 3.8.19)

Now please install the following necessary packages as instructed in the following sections.

3.3 Gymnasium

This is an open-source Python library for developing and comparing reinforcement learning algorithms by providing a standard API to communicate between learning algorithms and environments, as well as a standard set of environments compliant with that API. In the conda Environment create in the previous step added the gymnasium package

- To install the Gymnasium library use pip install "gymnasium[all]"

Fig.6. Gymnasium Package (Farama, 2024)

This step will install all the dependencies and supporting environment for the gymnasium package. For the use case of this project the existing MuJoCo environment which holds a simulation environment for many existing morphologies which will be later utilized in this project.

For the functioning of the principles of this thesis project a major aspect that enables an agent with intelligence is its trait of adaptability that comes from reinforcement learning, as discussed in section 1.3. This approach is of high importance for the successful execution of the concept of this project.

3.4 Stable baselines3

Fig.7. The Reinforcement Learning package Stablebaselines3 (Stablebaselines, 2024)

Stable Baselines3 (SB3) is a set of reliable implementations of reinforcement learning algorithms in PyTorch. It has existing development packages for Reinforcement Learning Application. It has support for all standard algorithms that can be customized and are available for training models. In the same anaconda environment use the following command to install the reinforcement learning package. This must be downloaded alongside tensorflow for smooth running of the project. Please use the following command in the conda environment, created in section 3.1

- To Install Stablebaseline3 use, pip install stable-baselines3[extra]
- The following command will install necessary dependencies to rum instances on GPU, conda install -c conda-forge cudatoolkit=11.2 cudnn=8.1.0
- Use the following command to install tensorflow, python -m pip install "tensorflow<2.11"

3.3 Python with CoppeliaSim API

Python is a versatile scripting language with usability in all domains of STEM subjects. And with existing software API it can be easily utilized for the existing use case of this project. As indicated in section 3.2, for this project python version 3.9 has been utilized. In addition, too all the packages installed in the previous sections an additional communication package called the ZeroMQ messaging library is necessary for this project

The ZeroMQ API provides sockets (a kind of generalization over the traditional IP and Unix domain sockets), each of which can represent a many-to-many connection between endpoints. Operating with a message-wise granularity, they require that a messaging pattern be used and are particularly optimized for that kind of pattern.

For the use of CoppeliasimEDU over the python package this API package can downloaded by using the following command in the anaconda environment

- Use this command in the command prompt pip install coppeliasim-zmqremoteapi-client

3.4 MuJoCO Simulation

Multi-joint dynamics are represented in generalized coordinates and computed via recursive algorithms. Contact responses are computed via efficient new algorithms we have developed, based on the modern velocity-stepping approach which avoids the difficulties with spring-dampers. Models are specified using either a high-level C++ API or an intuitive XML file format. A built-in compiler transforms the user model into an optimized data structure used for runtime computation.

Fig.8. MuJoCo Simulator (Google DeepMind, 2024)

The engine can compute both forward and inverse dynamics. The latter are well-defined even in the presence of contacts and equality constraints. The model can include tendon wrapping as well as actuator activation states (e.g. pneumatic cylinders or muscles). To facilitate optimal control applications and in particular sampling and finite differencing, the dynamics can be evaluated for different states and controls in parallel. Around 400,000 dynamics evaluations per second are possible on readily available models that can be downloads from the link provided in section 3.4. We have already used the engine in a few control applications.

This package is supposed to be installed outside the Anaconda environment. This can be done using by downloading zip file for the latest release via the link provided below.

- https://github.com/google-deepmind/mujoco/releases

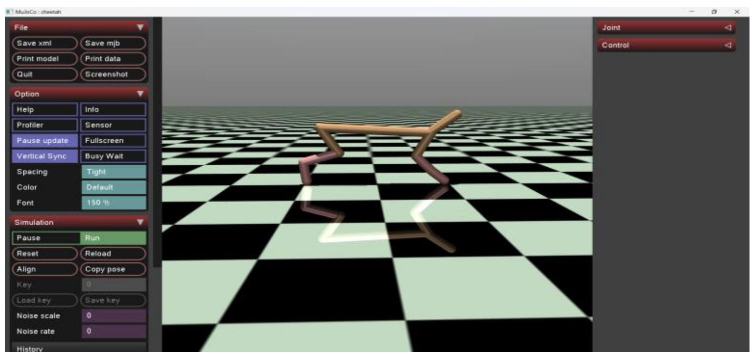

Fig.9. A half-Cheetah in the MuJoCo Simulator

Chapter 4

Implementation

This section is an explanation of the principles and implementations used in this project. There is an explanation of the package manager that is being utilized for creating a platform for the smooth function of the research. Then the use of learning strategy for the robot. Later in the section the creation of the morphologies has been discussed where principle of tail has been discussed.

4.1 Software development projects

4.1.0. First implementation on software

Initially an attempt was made to develop the objectives of this software on Coppeliasim Edu. The tool was considered good to implement the basic work of the project like design and testing the kinematics of the model but due to the lack of any reinforcement learning framework to support the learning aspect of the agent designed. The focus was shifted towards tools with pre-existing framework compatibility with the proposed software development model.

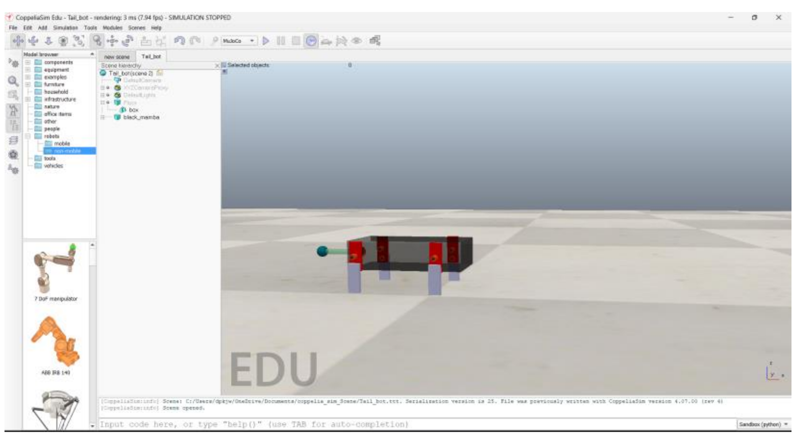

Fig.10. A quadruped developed in CoppeliaSim with 1–D pendulum as inertial correction system

4.1.1 Building a Compatible Environment

For the perfect execution of the scheme proposed in this thesis a dedicated software environment is required which shall be used to execute a smooth operation of the project. In this work a dedicated python environment is required to be created that support the packages as discussed in chapter 2.

The steps to build this environment have been discussed in section 3.2. For the success of this work a decision was made to work with python version 3.8.11. This is an earlier version of python which is stable and all the other packages compatible, are slightly older versions as well. Please note that an attempt to replicate the implementation of this project in a different environment will have complication as it has been noted in this work.

4.1.3 Stablebaseline3 to enforce learning

This is a readily available package on python. There are some reinforcements learning algorithms considered to be the best for research and project development such as TD3, PPO, HER etc. This package is free and open source that can be easily downloaded in an Anaconda environment

These algorithms will make it easier for the research community and industry to replicate, refine, and identify new ideas, and will create good baselines to build projects on top of.

From the implementation of (Huang, 2024) and (Yang and Hwangbo, 2024), it was observed that PPO currently provides good results for experimentations with similar objectives. Also, from the work of (Henderson et al., 2019) which can be considered as a pandoras box of knowledge from the scope of this project. Their work is full of detailed information creating a reinforcement learning pipeline for training agents in the MuJoCo environment.

In the work of (Henderson et al. 2019) where the authors have established multiple experimentations with reinforcement learning algorithms utilizing the MuJoCo environment. They have tested algorithms like TRPO, PPO, TD3 etc. And shared their results that consisting of some great findings. One of the best algorithms enforced for training an agent in the environment where gait motion is the optimal task to be learned is the TD3. This algorithm achieves the highest rewards out of all the algorithms generally use. But as the dynamics of the environment increases the efficiency of the algorithm decreases as it has been observed in (Henderson et al. 2019), here the results published have provided evidence that the PPO with slight changes to hyperparameter, outperforms TD3. Moreover, PPO appears to be more consistent across all the environment for learning different gait task.

Algorithm 1 Twin Delayed DDPG

Input: initial policy parameters θ, Q-function parameters ϕ_1, ϕ_2, empty replay buffer $\mathcal{D}$
Set target parameters equal to main parameters $\theta_{\text{targ}} \leftarrow \theta$, $\phi_{\text{targ},1} \leftarrow \phi_1$, $\phi_{\text{targ},2} \leftarrow \phi_2$
repeat
  Observe state s and select action $a = \text{clip}(\mu_\theta(s) + \epsilon, a_{Low}, a_{High})$, where $\epsilon \sim \mathcal{N}$
  Execute a in the environment
  Observe next state s', reward r, and done signal d to indicate whether s' is terminal
  Store (s, a, r, s', d) in replay buffer $\mathcal{D}$
  If s' is terminal, reset environment state.
  if it's time to update **then**
    for j in range(however many updates) **do**
      Randomly sample a batch of transitions, $B = \{(s, a, r, s', d)\}$ from $\mathcal{D}$
      Compute target actions

$$a'(s') = \text{clip}\left(\mu_{\theta_{\text{targ}}}(s') + \text{clip}(\epsilon, -c, c), a_{Low}, a_{High}\right), \qquad \epsilon \sim \mathcal{N}(0, \sigma)$$

      Compute targets

$$y(r, s', d) = r + \gamma(1 - d) \min_{i=1,2} Q_{\phi_{\text{targ},i}}(s', a'(s'))$$

      Update Q-functions by one step of gradient descent using

$$\nabla_{\phi_i} \frac{1}{|B|} \sum_{(s,a,r,s',d) \in B} \left(Q_{\phi_i}(s, a) - y(r, s', d)\right)^2 \qquad \text{for } i = 1, 2$$

      if j mod `policy_delay` $= 0$ **then**
        Update policy by one step of gradient ascent using

$$\nabla_\theta \frac{1}{|B|} \sum_{s \in B} Q_{\phi_1}(s, \mu_\theta(s))$$

        Update target networks with

$$\begin{aligned} \phi_{\text{targ},i} &\leftarrow \rho\phi_{\text{targ},i} + (1 - \rho)\phi_i \qquad \text{for } i = 1, 2 \\ \theta_{\text{targ}} &\leftarrow \rho\theta_{\text{targ}} + (1 - \rho)\theta \end{aligned}$$

      end if
    end for
  end if
until convergence

Fig.10. pseudo code for the TD3 algorithm (Open AI, 2024)

For my work, inspiration was taken from the accomplishments of (Henderson et al. 2019) and (Huang, 2024) and an attempt has been made to implement PPO to train the custom morphologies with mechanical tails for inertial control.

Algorithm 1 PPO-Clip

Input: initial policy parameters θ_0, initial value function parameters ϕ_0

for $k = 0, 1, 2, ...$ **do**

Collect set of trajectories $\mathcal{D}_k = \{\tau_i\}$ by running policy $\pi_k = \pi(\theta_k)$ in the environment.

Compute rewards-to-go $\hat{R}_t$.

Compute advantage estimates, $\hat{A}_t$ (using any method of advantage estimation) based on the current value function V_{ϕ_k}.

Update the policy by maximizing the PPO-Clip objective:

$$\theta_{k+1} = \arg\max_{\theta} \frac{1}{|\mathcal{D}_k| T} \sum_{\tau \in \mathcal{D}_k} \sum_{t=0}^{T} \min\left(\frac{\pi_\theta(a_t|s_t)}{\pi_{\theta_k}(a_t|s_t)} A^{\pi_{\theta_k}}(s_t, a_t), \;\; g(\epsilon, A^{\pi_{\theta_k}}(s_t, a_t)) \right),$$

typically via stochastic gradient ascent with Adam.

Fit value function by regression on mean-squared error:

$$\phi_{k+1} = \arg\min_{\phi} \frac{1}{|\mathcal{D}_k| T} \sum_{\tau \in \mathcal{D}_k} \sum_{t=0}^{T} \left(V_\phi(s_t) - \hat{R}_t \right)^2,$$

typically via some gradient descent algorithm.

end for

Fig.11. Pseudo code for the PPO algorithm (Open AI, 2024)

4.1.3 Farama Gymnasium: Play field for the agent

The most user friendly and versatile packages out there. This package can be used to build environment for implementation of some of the algorithms utilized in industrial and research purposes to train reinforcement learning agents. The package lets user implements some state of art algorithms Like PPO and TD3 to express issues in RL. For the scope of our project, using the PPO algorithms will be the best course of action as it was understood from previous work and has been discussed in the previous section.

```python
# Create environment
env = gym.make('Hopper-v4',xml_file = path_to_xml)# ctrl_cost_weight=0.1= ,xml_file = , reset_noise_scale = ....)
```

Fig.12. A snippet of using the Half-Cheetah in the gym environment

The illustration in Fig.9 is a representation of how an environment can be instantiated from the gymnasium package. Here half-cheetah environment with ‘ctrl_cost_weight’ being declared which penalises the agents for taking longer solution paths, this help in setting up the reward for the agent.

The next step will be to push the agent to gain traits for gait using the given environment. The morphologies of the agents for any given environment is fixed when the baseline is executed but a custom XML file can be passed to the environment. For the implementation of the principles presented in this project an attempt has been made to modulate the XML file to test the desired principles.

```python
# Create model with TensorBoard callback
model = PPO(CustomActorCriticPolicy, env, verbose=1, device = 'cuda', tensorboard_log=log_dir)

#instance for callback
callback = EvalCallback(env, best_model_save_path="./tb_logs/",
                        log_path="./tb_logs/", eval_freq=500,
                        deterministic=True, render=False)
# callback = SaveOnBestTrainingRewardCallback(check_freq=100, log_dir=log_dir)

# Train the model
model.learn(total_timesteps=500000,progress_bar=True, callback= callback)
```

Fig.13. Train an agent using the PPO algorithm by applying a custom policy

In the snippet above the agent is supervised as per the condition imposed by the Hopper-v4 Environment. Here a Custom Policy is being utilized which is fed to a PPO algorithm. A policy and Value network were assigned with this policy as it has been done in (Henderson et. al, 2019) to optimize the learning process. And certain hyperparameter tunning, have been inherited from (Huang, 2024). A callback was established to collect the best model depending upon the rewards achieved over the episodes. Then this model was saved and used for testing later.

Please note that the complete software created for this project has been shared in the Appendix section of this report please refer to it for in-depth insight of the software.

4.1.4 Crafting the Anatomy

The implementation of the principles of this work would have not been possible without altering the body of the agents to be trained. First an attempt was made to modulate the readily available baselines for the agents from (Google DeepMind, 2024). Here the morphologies for Half-cheetah, Hopper, Ant and Humanoid were chosen as the trait that an agent possessed in any of these four body-plan will have to learn to hop(jump), stand and walk as on bipedal like human, co-ordinate four pedals to balance while walking and attain the walk gait of cheetah.

Earlier in the thesis report the work from (Saab el at, 2018) was discussed (please refer to section 1.5). Here the authors explain about the ideal configuration for a tail and how to fabricate it. They propose many methods of inertial control system, but the principle of mechanical tail was the most interesting one. The morphologies achieved here were inspired from their work. The difficulty of constructing continuum tail is considered where high and an initial attempt was made to achieve the structure from XML modelling.

4.2 Structuring the learning

As discussed in the previous section the tunning of the parameter for the learning model was done as purpose by (Henderson, 2019). In their work they have purposed the Custom Policy Network which has been replicated in the implementation of this thesis. The values for other hyper parameters were tuned by replacing them in the command statement provided for PPO algorithm with the dependent parameter. This command syntax is actively available (Stable Baseline, 2024). These algorithms accept custom xml files to train an agent for any environment of choice. Thus, the modulated body plan undergoes the constraint set on the environment like the original body plan.

4.3 Complexity while Implementation

As the project was implemented, many nuances were encountered and the thus unsuccessful in achieving any presentable result. This report lacks a result section and has been replaced by an elaborated discussion with a brief conclusion, has been put up in the following section respectively.

Chapter 5

Discussion

In the animal kingdom the tail is one of the most peculiar appearing parts of animal's body plan and then it also appears to be the most important part of the anatomy for some of the beings possessing it. This is fine evidence of the engineering marvel of nature.

During high-speed pursuit of prey, the cheetah has been observed to swing its tail while manueuvring (e.g. turning or braking) demonstrates the potential of the cheetah's tail to impart torques and forces on the body because of aerodynamic effects, in addition to the well-known inertial effects. Same can be observed across different type of animal species. Thus, instigating the need to setup in depth research in the field which will help the multi-diverse gait motion for the animal.

The same can be observed across many other species of animals were the tail acts as an inertial control system in biological organisms. If we revise and address the objective as discussed in section 1.6. and recall the work from (Saab et al. 2019), the authors have proposed four base models for an ideal mechanical tail with different DoF. An attempt has been made to follow the principle from their work for designing the tails.

Fig.14. A planner Pendulum(1-DoF) and a 2-D (2-DoF) spatial pendulum.

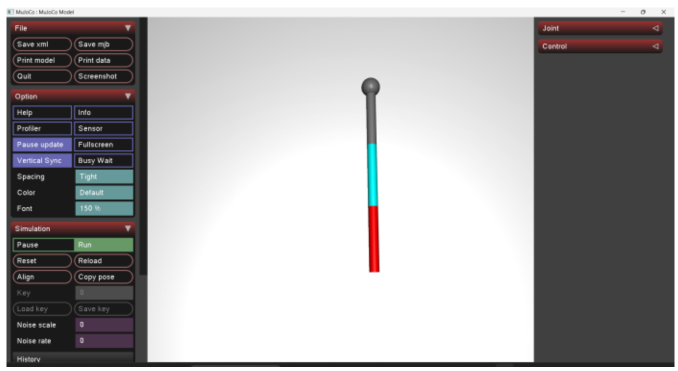

Fig.15 This is a 3-DOF mechanically articulated tail.

The objects capable of articulations, illustrated in the Fig.14 and Fig.15 have varying degree of freedom. These designs were developed within the scope of the project to be used as mechanical tail. There is a blob at one of the terminals of the tail which is an inertial mass suspend to counter the forces acting on the whole rigid body.

These designs are attached as tail on different location over the morphology to find the location that will provide the knowledge of most optimal positioning for any morphology to house inertial control system for the different task as it is studied in evolutionary systems. This will also provide insights into how the evolution of an any given species took place for periods of eons. This may also provide with insight into how the morphologies may change in the future or what may be the next step in the evolution cycle of that given species.

There is a very interesting and a widely spoken of design that has been proposed in the work of (Saab et al, 2018) it is the continuum design. The realization of the design was very difficult and keeping in mind the scope of this project and the time constraint, this design was not considered to be studied in this project. Though the work of (Saab et al, 2019) has valuable insights on how to design and implement it, the principle of continuum tail can be considered for future works.

From all the literature studied to gather insight on the topic it was understood that the mechanical tail proposed in this work greatly increases the workspace and provide multi-axis enhanced performance capabilities. Despite the achievements accomplished from creating a mechanical tail the design is still not optimal to provide precise control and full range of capabilities.

For most vertebrate animals, tail plays an important role for their morphology, providing variant functions to expand their mobility, as it has been discussed throughout this work. They play a vital role for building an inertial balancing system. The creation of such mechanical system will not only assist other mechanical systems to maintain balance and achieve an aligned gait, but it has high usability for living being. As such systems have been addressed in (Floreano and Mattiussi, 2008) as robots for biology where, robots are being adapted within the anatomical structure of living organisms to maintain the working of these systems.

The inertial control system discussed in this report can be utilized for rehabilitation of people with temporary or permanent walking disability like for athletes or accident survivor with movement disability. In this case the patients can wear a robotic tail around their waist or as a backpack over their shoulder. Over due course of time and with assistance from human physiologist the patients will recover their walking ability. Some individuals may suffer from Acute or Chronical Vestibular disorder. They may suffer from vertigo or walking disorder. Such individuals can benefit from the concept of mechanical tail to correct their gait.

In zero gravity all bodies are freely suspended and there is no inertial control over such objects. As humans ventures into space, for instance the international space station where there are many scientists and engineers working for long periods at time for months can utilize an additional limb to mount it onto a handle and use the hand for necessary task. Now they do not have to worry about drifting away from the work zone. Moreover, it can act as an additional limb that can be used to lift light load maybe like a coffee cup. The same inertial correction system will help them on earth to adjust to walking all over again. Thus, adaptive morphologies are a promising solution for designing multifunctional devices (Mintchev and Floreano, 2016)

There are many more application where the concept of mechanical tail can be utilized to provide extra stability to the system. Such that it can be mounted on to existing robotic systems to achieve a stable gait motion. One such application can be to mount the system onto a wall climbing bot, similar to the one in (Floreano and Mattiussi, 2008), here the authors speak of a WallBot developed at MIT, this is a wall climbing bot that is cable of climbing the wall. This robot has been inspired by the gecko, a reptile that can climb elevation with ease. These robots can have artificial setae in their feet, just like a gecko, that will act as a natural adhesive (Floreano and Mattiussi, 2008), making them capable of climbing wall. Bots with wall climbing capabilities are slow and it is difficult to steer them on the wall. Such robots can utilize a tail for extra assistance to steer them on the wall as well as provide them addition stability.

The manipulator as a tail, which was discussed in the work of (Huang, 2024) and (Yang and Hwangbo, 2024) is an excellent idea to put to use an existing payload for another task, thus increasing the usability of the manipulator, is aligns with the concept proposed in (Mintchev and Floreano, 2016) for adaptive morphologies. The manipulator already has a gripper attached to the arm that can also be used for grasping. Such multi-tasking augmentation to the body of the robot can increase the overall usability of a robot in multiple domains while making them more versatile.

Suppose the morphologies proposed in the (Huang, 2024) and (Yang and Hwangbo, 2024) can be perfected if future work is done on the concept. Then the manipulator as tail will make the robot more agile, capable to making maneuverers at high velocity, can be introduced in police forces where the robot can chase down convicts at run. Combined with abilities to climb wall like WallBot (Floreano and Mattiussi, 2008) and jump (Saab, 2019). The manipulator as a tail can be equipped with a taser gun that will subdue those offenders. As usual the 'manipulator comes handy!' to lift light to medium weight goods. Thus, help the people who are putting their lives in danger for us. This robot can also be introduced in defence services to carry load in rough terrain and much fast due to the introduction of the mechanical tail.

The major challenges encountered in this domain in achieving an ideal design and suitable control system. For the work of (Saab et al, 2019) it was understood that there are different design approaches that can be engineered as solutions for inertial adjustment mechanisms and can be categorized based on their principles of operation:

- substrate interaction mechanisms propel the surrounding environment to produce propulsive forces such as thrusters, gas jets, fins, turbojets and turbofans
- translational mechanisms displace a reaction mass to adjust COM location
- symmetric rotational mechanisms provide a reactive moment (no forces), such as reaction wheels to adjust orientation
- asymmetrical rotational mechanisms, such as pendulums (i.e. robotic tails), provide COM adjustments and generate control forces and moments.

From the perspective of this project there was another mechanism that was well studied but not considered due to its limitation, this method is the reactive wheel. The reaction wheel consists of an axisymmetric mass that is capable of continuous rotation about a single axis of rotation and is used to impart a reactive moment of its attachment point. Although they can be designed to fit in small volumes, they are limited by the angular velocity of the actuator and mass constraints. But from the work of (Saab et al,2019) it was understood that less torque is required for the robotic tail motion because the inertial force at the tail base also contributes to the net torque relative to the system COM and moreover the motor needs to run at a much higher speed in the reaction wheel case thus, for the same net force more energy is dissipated. Hence, it was considered that the mechanical tail is a better approach for creating an inertial balancing system.

Chapter 6

Conclusion

Bio-inspired systems play a vital role in upgrading the current robotics systems to address the concern of introducing intelligence. Such systems have been studied in the past and advancement are taking place with focus on building adaptable systems. The scope of application for which they can be employed is immense and the capability of such systems to address the primordial task objectives can been improved by a huge margin. The outcome to be drawn from this report is drawing inspiration from the solutions discovered via natural tinkering may be particularly useful for finding operational compromises to multi-optimization problems. Besides the fact that numerous sensors, actuators or control architectures in animals are often still more efficient than the artificial devices they have inspired–either for reasons tied to technological limitations or to lack of biological knowledge– perhaps the principal reason for the superiority of animals over robots lies in their greater degree of integration.

In the work described so far, there has been a tendency to evolve control system for pre-existing robots: the brain is constrained to fit a particular body and set of sensors as it has been discussed in all the literature about evolutionary robotics. And as it has been implemented in this work where a proposed anatomy is integrated with a physical intelligence paradigm and then the body is supposed to learn to utilize this new augmentation. As it has been discussed throughout section 1 that the core concept of intelligence cannot be defined without learning and adaptation and thus, the utilization of Reinforcement learning algorithm.

There has been works in the past that have encompassed the principle of evolutionary robots in their implementation principles. At the core of the topic is the concept of imitating the process of evolution of biological organisms and building adaptive system, who's behaviour for the environment is learned from episode of computational learning. From the literature read on the topic it was necessary for the survive of the agent to build strong communication with its surrounding by sensory and motor interactions.

Therefore, in this work an attempt had been made to create a robotic agent that will work in accordance with the principles of the concepts that have been discussed in this report. The simulation world implementation is an effective way to understand how the agents might work in the physical world and understand the action reaction pair the govern the scheme proposed for the mechanical inertial control systems. Moreover, the system principle is such that the functioning of the system as whole depends on the sense-think-act principle that the agents inherit by adapting to the environmental constraints.

The principle of mechanical inertial system has been a topic of high importance for researcher as they focus on making more accurate and precise motion planning systems that will provide the agents with capabilities to steer and navigate in difficult terrains. Current day robots require to be more adaptive when it comes to unseen environment. These robots can easily carryout task objectives by adapting to the complexity of the control problem to solve it. Thus, with a greater degree of integration of sensory motor system the robot will achieve greater degree of freedom and can easily co-exist with human i the environment where they have to work together. This will create a safe work environment where; while performing a tricky task the robot will have more control over its movement capabilities and the harm that the robot can cause to the environment will be reduced by a greater degree.

The project compelled me to dive deep in research work in-order to familiarize myself with the concept of physical intelligence. The terms bio-inspired and evolutionary robotics are special topic in this domain that have highlighted some of the key principle that will foster the robots for the generations to come. Both the domain of study complements each other to decipher how bodies can create intelligence and interact with their environment. As the new robots are extensively being integrated into daily human lives it is essential for them to possess abilities to perceive, control, act and learn. They must perform complex and unstructured tasks in the real-world while in the presence of humans. Thus, the concept studied to formulate this thesis report facilitates a tight coupling between an agent's body and brain.

I shall like to conclude this work by escalating the benefits of the proposed scheme. The concept itself is very undermined with a very few real-world robots utilizing the mechanical tail and co-existing with humans in operation. The research and work happening in regard to the topic are only taking place in the laboratory but are not being realized into real world application. With extensive research in the domain, more perfected design concepts can be achieved and with advancement in control algorithms the trajectory of the mechanical tail can be mastered which will help in introducing stability and provide more dexterity to the anatomy of the robotic system it has been mounted onto. Also as discussed in the previous section the concept has usability in healthcare sector where it can be utilized in rehabilitation for people with vestibular disorder or movement related disorder. There can be addition sensory system attached on the body of the robot to make it capable of interacting with its environment to perform addition task like manipulation and further assist humans by providing them with additional limb to engage with their environment to increase their capabilities in the workspace.

The scheme of building such a system shared in this project cannot be considered the best as this is just a prospect that was created from what was learned from the literature that was reviewed for this report. This paradigm shared here is not the best approach as there are limitations in this work. The design that was opted cannot be considered optimal. Further research into the design strategies will enable capabilities for distributed motion in the work about the mechanical tail. As the concept has been limited to simulation work and the objective to realize it into real world was never achieved, hence the power consumption of the actuation mechanic is unknown. In the sim the forces that act on the links governs its motion. And then the strength of the material used to create the whole mechanisms plays an important role in deciding the proper functioning for the mechanical system. Moreover, the designing algorithms for maneuvering that also account for the stability of the system can be compromised during tail motions. Designing algorithms for computing an optimal tail trajectory with a constrained workspace that considers the effects of both inertial forces and moments to maximize desirable effects of inertial adjustment.

Thus, further research into the domain of design and control algorithms can provide better results and can create a robot where it served to better compensate for the gap that still separates a robot from a living animal, with the introduction of better morphology and adaption policy. As this will benefit in the fields of research in space and exploration and assist in the safe introduction of robots in the everyday life.

The work incorporates the use of reinforcement learning algorithms, which as discussed in this work is vital in the creation of the systems that can adapt to the environment utilizing the feedback from the sensory motor feedback that it receives. The principle aligns with the concepts of evolutionary robots and the genetic programming.

In this work as discussed with reasonable proof that from the scope of this project the PPO algorithm is essential for training an agent in the sim world. But with advancement in AI new and better algorithms are being test and introduced in robotic systems. With more experimentation on this research work better algorithms can be put to use such as TRPO or the existing use case can be improved by testing the algorithms with better parameter tunning.

Robotic mechanical tails have potential to enhance the stability, maneuverability and propulsion of mobile robots by providing inertial adjustment capabilities and can demonstrated significant technological advances to the field of robotics in general with recent applications demonstrating manipulation. Despite the achievements accomplished with robotic tails, based on the current state-of-the-art, significant challenges still persist in regard to mechanical design, modelling and control to provide a full range of capabilities based on tail usage

References

Anaconda Navigator, 2024, Anaconda.Inc, Available at https://www.anaconda.com/ [Accessed on 08/04/2024]

Cangelosi A., Bongard J. Fischer N.H, Nolfi S. (2015). Embodied Intelligence. In J Kacprzyk & W. Pedrycz (Eds.), Springer Handbook of Computational Intelligence. Springer, p. 697-714

Casarez, C.S., Fearing, R.S., 2018. Steering of an Underactuated Legged Robot through Terrain Contact with an Active Tail, in: 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). Presented at the 2018 IEEE/RSJ International Conference on IntelligentRobots and Systems (IROS), IEEE, Madrid, pp. 2739–2746. https://doi.org/10.1109/IROS.2018.8594384

CoppeliaSIM, 2024, Coppelia Robotics AG., Available at https://www.coppeliarobotics.com/ [Accessed On 10/07/2024]

Dario Floreano, Francesco Mondada, Andres Perez-Uribe, and Daniel Roggen, Evolution of Embodied Intelligence, Embodied Artificial Intelligence (2004) pp293-311

Dario Floreano, Claudio Mattiussi (2008), Cambridge, Bio-Inspired Artificial intelligence, The MIT Press

Henderson, P., Islam, R., Bachman, P., Pineau, J., Precup, D., Meger, D., 2019. Deep Reinforcement Learning that Matters.

Huang, H., Loquercio, A., Kumar, A., Thakkar, N., Goldberg, K., Malik, J., 2024. Manipulator as a Tail: Promoting Dynamic Stability for Legged Locomotion.

Issac Sim, NVIDIA Corporation, 2024, https://docs.omniverse.nvidia.com/isaacsim/latest/overview.html [Accessed on]

Josie Hughes, Arsen Abdulali, Ryman Hashem & Fumiya Iida, Embodied Artificial Intelligence: Enabling the Next Intelligence Revolution, International Workshop on Embodied Intelligence 2021, 1261012001, Available from https://iopscience.iop.org/article/10.1088/1757-899X/1261/1/012001

Omari, M., Ghommem, M., Romdhane, L., Hajj, M.R., 2022. Performance analysis of bio-inspired transformable robotic fish tail. Ocean Engineering 244, 110406. https://doi.org/10.1016/j.oceaneng.2021.110406

Miriyev, A., Kovač, M., 2020. Skills for physical artificial intelligence. Nat Mach Intell 2, 658–660. https://doi.org/10.1038/s42256-020-00258-y

MuJoCo Sim, 2024, Google DeepMind MoJuCo, https://github.com/google-deepmind/mujoco [Accessed on 15/07/2024]

Pfeifer, R., Bongard, J., Grand, S., 2007. How the body shapes the way we think: a new view of intelligence. MIT Press, Cambridge, Mass.

Rudin, N., Hoeller, D., Reist, P., Hutter, M., 2022. Learning to Walk in Minutes Using Massively Parallel Deep Reinforcement Learning.

Sutton, R.S., Barto, A.G, 2018, Reinforcement Learning: An introduction, The MIT Press, Cambridge, MA

Saab, W., Rone, W.S., Ben-Tzvi, P., 2018. Robotic tails: a state-of-the-art review. Robotica 36, 1263–1277. https://doi.org/10.1017/S0263574718000425

Shapiro, Lawrence and Shannon Spaulding, "Embodied Cognition", The Stanford Encyclopedia of Philosophy (Fall 2024 Edition), Edward N. Zalta & Uri Nodelman (eds.), Available from https://plato.stanford.edu/cgi-bin/encyclopedia/archinfo.cgi?entry=embodied-cognition [Accessed on 21/08/2024]

Siciliano, B., Khatib, O., 2008. Springer handbook of robotics. Springer, Berlin

Spinning Up, 2024, Open AI, Available from https://spinningup.openai.com/en/latest/index.html [Accessed On 20/07/2024]

Stable Baselines3, 2024, Stable Baselines https://github.com/Stable-Baselines-Team/stable-baselines [Accessed on 24/03/2024]

Tang, Y., An, J., Chu, X., Wang, S., Wong, C.Y., Au, K.W.S., 2023. Towards Safe Landing of Falling Quadruped Robots Using a 3-DoF Morphable Inertial Tail, in: 2023 IEEE International Conference on Robotics and Automation (ICRA). pp. 1141–1147. https://doi.org/10.1109/ICRA48891.2023.10161422

Yang, Y., Norby, J., Yim, J.K., Johnson, A.M., 2023. Proprioception and Tail Control Enable Extreme Terrain Traversal by Quadruped Robots.