ME 425 HW 1

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In this report, different kinds of mobile robots and their significance for mobile robotics will be investigated. A bibliography section containing citations to all used articles can be found at the end of the report.

1 Legged Robots

1.1 ETH Zurich's ANYmal

[Hutter et al., 2016]

This legged robot that was developed by ETH Zurich was one of the first robots that combines high mobility with the capability of dynamic locomotion. It is also designed completely to operate on an outdoor environment with little to no intervention from humans. It was specifically designed so that it can operate for a long time in challenging environments such as extraction sites or after natural disasters. Currently it can run for over 2 hours autonomously before needing to recharge. Now let's dive a little deeper into the technical specifications of the robot:

- ANYmal is a quadrupedal robot that is about 0.5 meters tall, 30 kg in weight and resembles a dog.
- For locomotion, it has 3 joint units for each of its legs (so 12 joints in total). Using a joint unit system like this has several advantages such as the robot not having any other components on its legs etc. The robot benefits from an attachable head which allows it to have different kinds of modules for perception of the environment so that it can adapt to different kinds of scenarios more effectively.
- For actuation, it implements a series elastic actuation method with a rotational spring, similar to the SLIP model that we have covered in class. This enables it to be much more stronger/ durable and have a much smoother motion. To receive the information from the legs, absolute position sensors that measure joint output position (in degrees) and rotational spring displacement are used. To control the motion, a control loop that controls both position and torque is implemented.

1.2 Boston Dynamics' Atlas

Note: Since there is little to no detailed information on this robot on the web, only the kinematics and its control system will be discussed here. All information is taken from [Kuindersma et al., 2016]

The Atlas robot, developed by Boston Dynamics is a hydraulically powered humanoid robot with 28 degrees of freedom in total. This makes it a pretty hard system to control and make it perform complex actions. Boston Dynamics solved this problem by designing a control system that is comprised of three different phases. Motion Planning, Control and State Estimation:

1. In motion planning phase, the goal is to create a mapping of the environment and detect which spaces in the environment are suitable to be stepped on. First of all, a Lidar scan is used to get the distance data and then generate the map and identify obstacles in environment. Then an an optimization problem is solved to determine the sequence of footsteps (their position etc.) such that the robot can move to its destination in a stable manner. The robot also has a whole body controller as well for more complicated and quick motions. After determining this sequence, a trajectory for the center of mass of the robot is computed and transferred to the controller.

2. The controller then determines the accelerations for each body part. These are then fed into a Quadratic program along with the cost to go function(which is the cost to get back on the original trajectory)

3. The state estimator then modifies the feedback signal by integrating the sensory data that comes from Lidar, vision etc by using Kalman filters.

All this control mechanisms allows Atlas to be able to do many complex action suh as walking, balancing carrying weights traversing slanted or rough terrain etc.. This project is important for mobile robotics as it shows that even such a complex robot with complicated kinematic systems can be controlled in a manner such that it will be able to perform complicated tasks.

1.3 MIT Cheetah

[Bledt et al., 2018]

This quadruped robot developed by MIT is designed to traverse uncertain terrain usually in high speeds in a dynamic fashion. The robot is electrically powered with high torque actuators connected to a planetary gear for reduction of torque. The robot has 3 degrees of freedom per leg. This enables it to have a much greater degree of mobility compared to its predecessors. Its legs are also highly capable in terms of force, with it being able to exert forces of up to 700 N magnitude.

In terms of its control system, the robot has a low level and high level control system. The low level control which controls things like motor inputs and low level leg controls are able to run on a much higher speed than full locomotion control.

The high level control architecture is much more complicated than the low level control:

1. Gait Control: This part of the mechanism determines which gait to be used during locomotion. The default gaits are made such that they would mimic the natural movement patterns of animals. These default gaits can then be modified to fit the environment that the robot is in based on the contact detection algorithm (which calculates the probability that each leg is currently in contact with a surface depending on encoder data, estimated force etc.).

2. Force Control: When the legs are in contact with the ground, force contact is used to make the COM stay in the area between the legs as to maintain balance and also to calculate the forces needed for the actuation of the desired trajectory.

3. Position Control: When the leg is in the air, the robot needs to estimate the position at which the leg will again make contact with the ground and adjust the foot position to be able to make this contact safely. After the desired robot leg pose is determined, this information is sent to an inverse kinematics solver to be able to determine the amount of actuation for each motor. They are then realized at the motor level using a PD controller.

The control algorithm also utilizes state estimation to correct for any potential errors that might have occurred during the other parts of the control mechanism. The state estimator uses a sensor fusion algorithm by using the data from the IMU and accelerometer values.

1.4 Stride Bipedal Robot

[Huang et al., 2024]

Stride is a simple, open source and easy to manufacture bipedal robot. The entire mechanical and electronic documentation can be found open source on the internet. This makes it one of the first robots in its field that is quite easy to manufacture and use, even for a novice in mechatronics/ engineering.

As for the mechanics of the robot, it is made of relatively easy to find and versatile materials. It is constrained with a central beam that prevents any lateral movement of the robot. Each leg of the robot has 2 actuated joints, one for the hip and one for the knee. As for the actuators themselves, goBILDA (84 RPM, 93.6 kg·cm)s are used.

For the electrical components of the robot, a Raspberry Pi and a Arduino Mega is used as the high level and low level controllers. As for sensors, two IMU s are used. One is mounted at the hip to track the motion of the leg and the other is mounted at the central bar as to track the general angular velocity of the robot. The feet of the robot also has contact sensors to track the ground contact.

The software of the robot is developed in ROS2. Most of the code is in C++ with Eigen library utilized for linear algebra operations. At the low level, the IMU, contact sensor and motor controller data is processed and sent to the Ros2 locomotion controller node. It is then processed here and a step planner and a output controller then determines what kind of actions to take to move the robot in the desired trajectory. The full electrical and software system is represented in Figure 1:

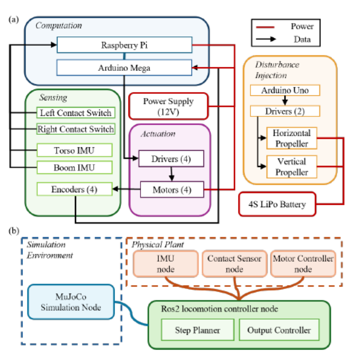

Figure 1: (a) Electrical components and wiring topology. (b) Software architecture, in which the ROS2 controller node can be customized by the user.

1.5 Fifth Robot

2 Wheeled Robots

2.1 HelpMate@: A Robotic Courier for Hospital Use

[Evans, 1994]

This mobile robot was developed as to be able to make the transportation jobs in hospitals much easier and cheaper. Since this robot will take care of arbitrary tasks like bringing food to patients, transporting sterile equipment to and from the patient rooms etc., The actual hospital staff will be able to take their time performing more important tasks. It was also the first mobile robot to be used in hospitals.

The robot uses a navigation system similar to the one we covered in class however it is much more complicated and it uses several sensor fusion techniques to reduce any errors it might get by just using odometry. In total, the robot has 4 differnt modules in its navigation algorithm:

1. The encoder information on the robot's wheels is intagrated over time to obtain the pose information of the robot. This is part of its navigation module called "Dead Reckoning".
2. Alongside this, the robot also uses other sensory information such as sonar, infrared and vision based sensors such as a camera to track its vicinity and do path correction by utilizing the nearby landmark objects. This mode is called "Registration".
3. In addition to this, it also has a mode called "Path Following" which allows it to move parallel to the walls in a corridor.
4. The final mode of the robot's navigation algorithm is "Obstacle Avoidance". This mode runs concurrently with the path following algorithm and utilizes the sensory data it receives to generate a local map of the robot. While moving in this path, if the robot detects any situation where it would collide with any object if it were to continue moving, it stops for a while and the module sends commands to the robot such that it will override its original trajectory as to avoid any collisions.

The robot also has the ability to use elevators, work in multiple buildings so long as they are connected by corridors.
Using this navigation algorithm, the robot can perform many kinds of movement patterns such as going to a single stations, making a round trip to end up where it started and also visit only a selected number of different stations.

As for the execution of its commands, it can either be programmed to execute certain navigation tasks during a specific time of the day or it can be prompted by a human to perform a predefined task.

2.2 Shakey The Robot

Shakey the robot was developed by SRI International in 1966. Shakey was the first autonomous mobile robot to utilize sensory data such as perception with the help of an external computer to have a much better perception ability of its environment compared to its predecessors. It was also the first mobile robot that could plan its actions and take those actions to reach complex goals and/ or to survive in realistic environments on its own. As hardware, it had some sensors like a TV camera to perceive its environment and an antenna to communicate with the external computer that did the higher computational actions like path planning and perception.

The main contributions of this project to mobile robotics are the A* search algorithm and Visibility graph used for path planning of the robot and the Hough Transform used in the Computer vision. A brief description of these methods are as follows:

- A* search algorithm is a path finding algorithm that finds the shortest path give a starting and ending point in a weighted graph where the weights of each edge is known. Its main working principle is by creating multiple paths(i.e. it maintains a tree of different paths for the tree) that emerge from the starting point and calculating whether to extend them or not by estimating the cost of the path if it were extended all the way to the goal point. It then does a series of computations to select the path that will minimize the cost between the two points on the graph.[Hart et al., 1968]
- The Hough Transform is a Computer Vision method used to determine simple shapes in an image like lines and circles. The advantage of this algorithm is that it can detect these patterns even if the image has gaps or some other noises etc.. [Duda and Hart, 1972]
- Visibility graph is a method for transforming a path finding problem into a searching problem in a graph. It does this by using several geometric transformations on the local map. The generated map is then used by the path finding algorithm to find the shortest path to the destination [Lozano-Pérez and Wesley, 1979].

2.3 Nasa's Perserverence Rover

2.4 Nasa's Curiosity Rover

2.5 Fifth Robot

3 Flying Robots

3.1 NASA's Ingenuity Helicopter

The Ingenuity helicopter developed by NASA operated on the mars surface from 2021 to 2024. It was initially a part of the Perserverance rover and was transported to mars under this rover. The robot was originally made to make five flights. It exceeded this number by a long shot by making over 70 flights. This robot was an important point in aerial robotics as it demonstrated that such flying robots can be operated long term even in harsh and thin atmosphere environments like Mars and paved the way for future aerial exploration on such extra-terrestrial bodies.

The vehicle, coming in at a weight of about 1.8 kg and a size of 121 cm $\times$ 49 cm $\times$ 52 cm, was powered by solar panels. It stored the energy it collected during the day in its 42 Whr battery. At night, it remained in a "SLEEP" mode, where its power consumption was minimized.

Since sending signals from Earth to Mars would take several minutes, the robot was designed such that it could operate autonomously on its own. It ran on an operation cycle which was programmed into its internal components. It first planned the trajectory, landing site, flight time etc. about the flight and then it manages the flight and sends the flight data analysis after the flight back to earth.

As time went on, Ingenuity took on much more dangerous and longer trips on the surface of Mars. This can be seen from its flight log as well. [Tzanetos et al., 2022]

Flight	Sol	Horizontal Distance (m)	Altitude (m)	Max. Groundspeed (m/s)	Duration (s)	Total Accumulated Distance(km)
1	58	0	3	0	39.1	0
2	61	4	5	0.5	51.9	0.004
3	64	100	5	2	80.3	0.104
4	69	266	5	3.5	116.9	0.37
5	76	129	10	2	108.2	0.499
6	91	215	10	4	139.9	0.714
7	107	106	10	4	62.8	0.82
8	120	160	10	4	77.4	0.98
9	133	625	10	5	166.4	1.605
10	152	233	12	5	165.4	1.838
11	163	383	12	5	130.9	2.221
12	174	450	10	4.3	169.5	2.671
13	193	210	8	3.3	160.5	2.881

Figure 2: Ingenuity Flight Log

3.2 Agilicious

[Foehn et al., 2022] Agilicious is an open source quadrotor robot developed by ETH Zurich's Robotics and Perception research group. It has a high thrust to weight and torque to inertia ratios making it quite agile as most quadrotor flying robots are. It being open source makes it extremely useful for doing research, as any project done on it can be easily verified or reproduced by other people.

One of the biggest problems that Agilicious overcame was the problem of high problem vs. computing power problem. Normally, adding more computing power usually increases the weight of the robot, which makes it cumbersome. However, on Agilicious, there is an integrated GPU to its system, allowing it to run neural network architectures and neural network based controllers, in addition to model based ones. This allows it to have high computational power with a compact design. Now, let's take a closer look at the technical details of the robot:

3.2.1 Computer Hardware

As the main computer that will be used for high level tasks like estimation, planning, optimization-based control, neural network inference etc.; NVIDIA's Jetson TX2 embedded AI computing board was used. Criteria such as size, weight, presence of a GPU was taken into account when making this decision.

For the low level flight controller, a low level flight controller under the name agiNuttX was developed for the robot. The software can be ran on many embedded microcontrollers such as STM32F4. The original hardware used in the robot is also custom made, though it is quite similar to currently available BetaFlight controllers.

3.2.2 Flight Hardware

For the main frame, The Armattan Chameleon 6 inch frame which is made out of carbon fiber was used due to its lightweight and durable design. Many of the other parts of the robot were custom manufactured and 3D printed.

3.2.3 Sensors

The main types of sensors that were used were IMUs and cameras, combined to make a vision+ odometry based perception.

3.2.4 Software

The software consists of two main parts, an agilib librry that utilizes c++ and Eigen library for linear algebra. The second part is a ROS wrapper that allows for integraton with existing components that work with ROS. Under the main library, there is a pilot that has the main logic unit for flight control. There is also a pipeline comprised of modules like Estimator, Sampler, Controller and Bridge. Although the technical details of all these modules won't be given in this report, all of these modules under the main library work together to be able to stabilize the drone and keep it on the desired trajectory that is designated by the user.

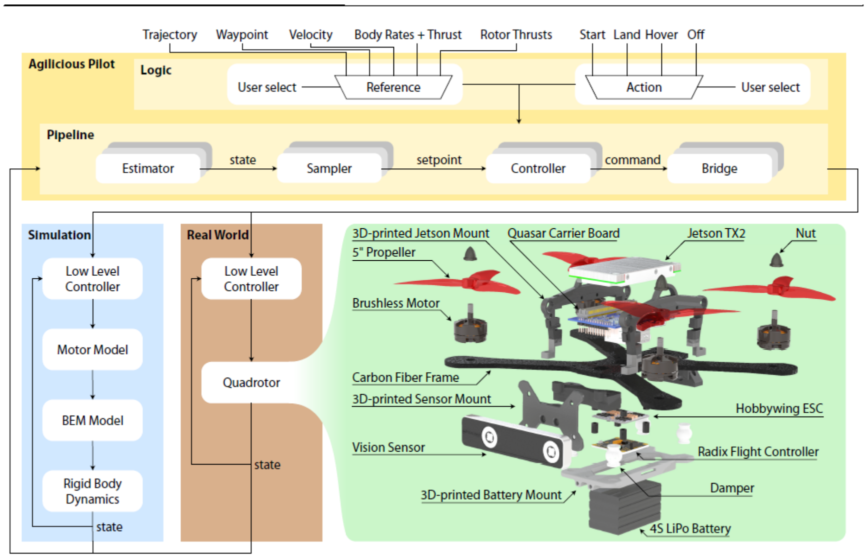

Figure 3: Agilicious Software And Hardware Structure

3.3 Nasa's Global Hawk

[Naftel, 2009] Global Hawk is a fully autonomous unmanned aerial vehicle that is developed by NASA.The vehicle operates based on a mission plan that is given to it beforehand. The main advantages of this vehicle is that it can carry quite heavy loads to extremely high altitudes and it can stay there for very long times (about 30+ hours). It is currently one of the longest endurance autonomus aerial vehicles in the world.

3.4 Fourth Robot

3.5 Fifth Robot

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