Design and analysis of a mobile robot for storage and retrieval system

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Abstract. The growth of the automation industry has been staggering and its continued growth has imbibed life to an aging industry. The application of robots has reduced the workload of humans and frees up the workforce off of monotonous, non-creative jobs and can be efficiently utilized for more fulfilling jobs. The aim of this research is to design and analyze a mobile robot for a storage and retrieval system. The robot has the objective of translating long racks in storage houses to different locations, instead of transporting the individual components in the racks. The main task of lifting the racks will be accomplished using a lead screw mechanism and a differential drive is used as the main drive. The challenges faced were mainly, distributing the load concentration equally along the chassis to ensure maximum stability and limiting the weight ratio of the robot to the racks to an optimal number. Design and analysis of the robot were carried out using CATIA and ANSYS, respectively.

1. Introduction

Technological advancements are no longer measured in decades. Decades have been converted to years and years to days. The field of artificial intelligence and robotics has been progressing at a blinding pace and is "the happening" field in technology. The main aim of a robot is to assist a human in his/her work, make it easier. The application of robots has reduced the workload of humans and frees up the workforce off of monotonous, non-creative jobs and can be efficiently utilized for more fulfilling jobs. The kiva robots used in Amazon's fulfillment centers are a high end technology that emphasizes on improving efficiency via highly stable operation. It has revolutionized ASRS systems by transporting the whole rack instead of transporting individual components housed in the racks. This study has derived inspiration from Amazon's technology.

This research aims to design and analyze a mobile robot [1] for a storage and retrieval System. The main chassis of the robot is designed in a way, as to assure maximum stability at all times, both during mobile and stationary conditions. The mechanism used for lifting the racks is a combined lead screw and spur gear mechanism. The lead screw is used to facilitate vertical lifting and incorporate rotation about Z-
axis to the lifting platform. The spur gear is used to couple the motor to the lead screw, to provide actuation. An in-depth calculation was carried out during the study for the design of the lead screw and spur gear. A differential drive is incorporated as it provides high mobility and a wide range of motion for the robot. Mainly, a differential drive allows the robot to have a zero-axis rotation, which is integral to maintain high efficiency of operation and to reduce cycle time. A robot cannot have a differential drive without at least one more contact with the ground. Ball-Castor wheels are embedded into the chassis to provide a stable drive and avoid swinging of the chassis. The Castor wheel, along with the drive wheels are placed in a hexagonal arrangement to ensure the perfect distribution of stress from the robot to the ground.

The conceptual model of the robot is carried out in CATIA. On the completion of the designing phase, testing of the design was carried out via analysis on ANSYS. Various parameters such as deformation, mean stress, etc. were generated on analysis. There were various challenges that had to be overcome. The weight ratio of the bot to the payload had to be kept as low as possible to have a higher efficiency of operation. The highest amount of stability of the robot has to be ensured at all times, to safely secure the rack and its contents. The robot has to be a rugged system to withstand the constant and cyclic stress and have a long life, without affecting performance. The assembly has to be carried out in such a way that minimum maintenance is warranted. The robot needs to have a configured environment to be effective. The floor of the warehouse has to be flat and provide adequate friction. The racks that have to be lifted must be designed in a way, so as to allow the robot to enter under it. The various phases and components of this research have been discussed in depth, below. This paper begins with the design of the robot. A detailed study of all the components of the robot is presented. Design specifications have been explained. Following this, the electronic components and systems design of the robot will be reviewed and the specification of the robot will be presented. Finally, the research will discuss the results of the study and a conclusion based on this research will be described.

2. Design:

2.1 Chassis

The chassis of the robot is the structure that supports and houses the main mechanism and all the electronics powering it. It is the foundation of the robot and is responsible for handling the stress applied due to the input load on the robot. It is the structure that is responsible for handling the various forces experienced by the robot, either by distributing it internally or by transmitting it to the ground. It is also the structure that incorporates the drive motor and the wheels. It is the spinal cord of the robot, connecting the upper mechanism to the drive, transmitting forces. There are various factors that play a role in designing a chassis for a mobile robot.

2.1.1 Material

There are many traditional materials that can be used for building the chassis of a robot. Depending upon the specifications required of the chassis, a suitable material is selected. Aluminium is a very lightweight material and is highly ductile and machinable. It can withstand high amount of stress, depending on the shape, and has a high point of fracture. Depending upon the shape of the chassis designed, and its supporting structures, the load bearing capacity of a material can be maximized. It is economically feasible and is easily available. For the above mentioned properties of aluminium, it is selected as the material of construction for the chassis.
2.1.2 Shape

The shape of a chassis is the major factor that can boost the load bearing capacity of a material. The traditional shapes that a robot chassis can take are the basic square, rectangular, cross, y-shaped, etc. The shape of the chassis is chosen based on the type of stress acting on the chassis and the level of stress distribution that needs to be incorporated. An octagonally shaped chassis offers one of the best stress distribution factors of all shapes. The fact that is closer to a circle than the other traditional shapes, means that there are lower points of stress concentration. The edges of the octagon can be applied with fillets to eliminate any sharp corners. Stress usually gets concentrated or gets accumulated at sharp corners, so rounded corners have a better prospect of distributing it. An octagon is also a symmetrical shape, hence there is a higher flexibility in choosing the directional bearings of the robot and the designer has more options to decide the placement of the drive motor and wheels.

2.1.3 Size

Size of the chassis is essential to the process of stress distribution and governs the mobility of the robot. The chassis for this robot has a box dimension of 55cm. The dimension has been selected after carefully factoring in the various problems that would occur for sizes that are either too big or too small.

The limitations of chassis that has a large size are:

- Chassis would be very heavy.
- Economically not feasible.
- The robot will be unable to enter the tiny space under the racks to lift them up.
- There would be a decrease in agility of the Robot for a particular actuator.

The limitations of the chassis that has a very small size:

- The chassis would not be able to maximize stress distribution.
- Chances of the toppling of the Robot are high, especially when motion is suddenly stopped.
- The system wouldn't be very rugged.

Keeping the above points in mind, an optimal size, that borders between the realms of 'big' and 'small', was finalized and an octagon with a box dimension of 55cm was selected. Rectangular beams, running between two opposite sides were also incorporated to provide stability and give a sturdy interior to the chassis. It would be the base for mounting the main lifting mechanism and also serves as a mediator to distribute the stress emanating from the load applied on the mechanism. Fillets can be applied to all the corners of the chassis to eliminate sharp corners. The chassis has been designed in such a way that, maximum stability is always achieved to balance the rack.

2.2 Drive

The drive used on a chassis determines the mobility of the robot. There are many types of drives used in robot, namely electrical, pneumatic and hydraulic. The use of each of these drives depends entirely upon the application of the robot. The mobile robot in this study uses a differential electric drive [2],[3]. It has two driven wheels. A differential drive allows the robot to have very high mobility and freedom of movement. It equips the robot with the ability to move in any direction on the X-Y plane. One of the main advantages of using a differential drive is its ability to perform 'zero-axis' rotation i.e, the robot is able to rotate about the z-axis which lies midway between the two drive wheels. This makes turning and cornering very efficient. A differential drive cannot exist or does not suffice on its own. Two points of contact is not enough to provide stability to the robot, as they are basically, two line contacts with the ground. A minimum of three line contacts or 3 point contact is necessary to achieve threshold stability to remain upright. Along with the drive wheels, 4 Ball-Castor wheels are used to improve the balance of the robot. The 4 castor wheels along with the 2 drive wheels are arranged in a hexagonal pattern, mainly owing to
the shape of our chassis, which happens to be a hexagon. The ball castors also help distribute the stress more effectively and to also reduce the load on the drive wheels. If the load on the drive wheels is distributed to the castor wheels, then the torque requirement of the drive motor decreases, enabling the robot to have a higher speed.

The drive motors are power window motors DC Motors. Power window motors have a high torque rating, but offer low speeds, which perfectly satisfy the robot's drive needs. The robot has to have low speed in order to balance the long racks and to avoid toppling. The wheels have a Nylon core coated with rubber for traction and dampening of vibrations. Vibrations have to be kept to a minimum for the robot to have a smooth operation. Silicon based rubber is the best suited for wheels used in robotic drive. Nylon is used as the core materials, owing to its better vibration dampening properties compared to metals and its low density.

**Specification of wheels:**
- Core material- Nylon
- Coated material- Silicon Rubber
- Diameter of core- 115 mm
- Thickness of Rubber coating- 5 mm
- Width of wheel- 20 mm

The shafts of the drive motors are usually not mechanically strong. The capacity of a motor shaft to handle stress, especially impact loads is very low. If mechanical failure occurs in the motor shaft, it will lead to a scenario in which the rack will definitely topple and get damaged. In order to avoid the failure of the motor shaft, the shaft is coupled to the wheel via a Circular Ball Bearing. The existence of this bearing ensures the redirecting of load from the shaft to the bearing, while also allowing smooth rotation of the shaft. The bearing is used on both the drive motors.

**Specifications of the Ball bearing**
- Internal Diameter- 10 mm
- Outer Diameter- 26 mm
- Width- 8 mm

The drive motors are directly coupled with the chassis to provide as stable a support as possible. The ground clearance of a robot has to be as low as possible so as to keep facilitate a low centre of gravity. A low centre of gravity ensures higher stability during the robot's Drive. A low ground clearance can be achieved by clever positioning of the drive motor and its wheels. The robot needs to have a low ground clearance for another obvious, but very important reason. The robot has to be able to go under a rack to be able to pick it up.

2.3 Lifting Mechanism:
The lifting mechanism is the main mechanism in the robot. It facilitates the actual lifting of the racks. There are a lot of options for the mechanism that facilitates vertical actuation. There are many factors that must be considered while selecting a lifting mechanism:
- Maximum load carrying capacity
- Speed, accuracy, and efficiency
- Actuation Length
- Maximum Torque produced.
- Stall Torque
- Noise
- Lubrication requirements
- Cost
There are a lot of mechanisms that can be used for the purpose of lifting. Some of them are lead screw, ball screw, spiral lift [4], driving pulley and rope [5], lifting jack [6], etc. They all have their own advantages and disadvantages. A detailed study has been carried out to compare each mechanism’s strengths and weaknesses to find the right fit to the robot's application.

But the aim of this process of lifting is not just vertical lifting. The mechanism must be able to incorporate a rotational motion about the z-axis, along with the vertical movement. Why is this necessary?

Let us imagine a mechanism that can only facilitate lifting the rack. In this case, after lifting the rack, when the bot is in motion and it wants to make a turn, the rack will also turn with the bot, with respect to the ground. This could destabilize the rack and make it loose balance. Hence, we need to create a situation in which, at all times, the relative motion of the rack with respect to the ground, about the z-axis is zero.

To achieve this, the lifting mechanism has to be able to rotate the rack as it lifts it. While lifting the rack, if the bot rotates in the anti-clockwise direction and the rack rotates in clockwise direction, keeping angular velocity of the bot and rack equal, the relative motion between them will be zero. Hence at no point of time, will the rack actually rotate. A combined lead screw and spur gear mechanism will achieve this task.

When the nut of a lead screw is rotated, then the lead screw will move up or down, depending upon the direction of rotation of the nut. But in this case, the lead screw will not have any rotation. The mechanism required to achieve the above described process needs to have both rotational and vertical motion. To achieve this, the nut is locked and the lead screw is given rotational actuation. This will ensure that the rack will rotate in either clockwise or anti-clockwise direction, depending on whether it is being lifted or dropped. When the rack is being rotated in the clockwise direction, the robot is rotated in the anti-clockwise direction with the same speed, rendering the rack stationary.

The lead screw cannot be coupled to the motor directly as the load transferred from the lead screw will be too much for the shaft of the motor, leading to a mechanical failure. To transmit motion and power from the motor to the lead screw in the most efficient way, without causing significant damage, a spur gear is incorporated in the design. Hence the lead screw is coupled to a spur gear which receives actuation from the motion. The actuating length of the lead screw is 10cm. In order to maintain a continuous mesh between the spur gear and pinion, either the gear or the pinion needs to be at least 10cm long. The pinion or the driving gear, in this case, is kept longer than the driven gear. If a decision has to be made, whether to keep the driven gear longer or the driver gear, a driver gear is a more logical option, as it has a smaller diameter and would hence take up lesser space and would not be heavy.

The nut that engages the lead screw plays a very integral part. The nut is the component that supports the whole lead screw in this mechanism. In order to bear the weight of the lead screw and the rack, the threads of the nut and the lead screw have to be big. The nut is stationary and supports the lead screw by meshing with it. A supporting structure for mounting the nut is welded onto the chassis. The structure also distributes the force and transfers the stress from the nut to the chassis. The required calculations [7], [8] were performed to obtain the following specifications.

**Specification of lead screw:**
- Material: mild steel
- Major Diameter, \(d_{major}\) - 100mm
- Pitch, \(p\) - 12 mm
- Mean diameter, \(d_m\) - 94mm
- Thread angle 2\(\theta\) - 20\(^\circ\)

![Figure 1. 3-D model of the robot in CATIA.](image-url)
Specification of pinion and gear:
- Material: mild steel
- Module, m - 3 mm
- Centre distance, a- 120 mm
- Face width, b- 12 mm
- Bottom clearance, c- 3.9 mm
- Tooth depth, h- 5.7 mm
- Pitch diameter:
  - Pinion, \( d_1 \) - 48mm,
  - Gear, \( d_2 \) - 192mm
- Tip diameter:
  - Pinion, \( d_{a1} \) - 52.8 mm
  - Gear, \( d_{a2} \) - 196.8 mm
- Root diameter:
  - Pinion, \( d_{r1} \) - 40.6mm
  - Gear, \( d_{r2} \) - 184.6mm

The 3-D model of the robot is designed using CATIA. An assembled view of the model is depicted in figure 1. The box dimension of the chassis is 55 cm and the total height of the robot is 30 cm. A lift of height 10 cm can be attained by the robot. Figure 2 illustrates the various components of the lifting mechanism. The nut is fixed using the supporting columns to the chassis.

3. Analysis
The analysis of the robot plays an important role in the process of designing the product. It provides the quantitative data about the levels of stress and deformation experienced by the robot due to the application of load by the storage rack. After comparing the experimental results with the properties of the material used to build the structure, one can estimate whether it would be effective in a practical situation or it would fail. If the robot is manufactured without any prior analysis, it would lead to mechanical failure if the design of the robot fails under the load. The analysis was performed in ANSYS, an analysis software. The first step in analyzing the design is to import the 3-D model created in CATIA to the FEA environment. The next step is to apply material properties to the structure. Moving further, the most important stage in analysis is meshing the whole structure. Meshing divides the body to a large number of integral elements. Meshing a body ensures uniform distribution of load to each element. The results of the Analysis would be more descriptive and detailed if the number of elements is high due to increased

![Figure 3. Tetrahedral mesh.](image)

![Figure 4. Equivalent von-mises stress analysis.](image)

![Figure 5. Total deformation analysis.](image)
resolution of the process. A tetrahedral mesh is created as it divides the body into a large number of elements. A load of 550 N is applied on the platform. The boundary conditions are set and certain components are fixed to carry out static structural analysis. The circumferences of the wheels, castor wheels and the shaft of the differential drive are fixed. The model is then solved for equivalent Von-Mises stress and total deformation. Figures 3, 4 and 5 show meshing and analysis results.

Analysis results:
- Maximum von-mises stress: 4.05 \times 10^7 Pa
- Ultimate yield strength of Aluminium: 9 \times 10^7 Pa
- Maximum Total deformation: 2.26 \times 10^{-6} m

Maximum von-mises stress < Ultimate yield strength of aluminium. Hence, the design is considered to be safe.

4. Electronics Subsystem:
The entire electronics of the bot is mainly based on single board computer acting as a master and an MCU (Arduino mega) acting as a slave which communicates through SPI (Serial Peripheral Interface). The system runs on three high torque dc motors out of which two of them are used for drive and one of them is for the lifting mechanism. Since the system is completely autonomous GPS sensor is incorporated for waypoint navigation. Ultrasonic sensors have been used for obstacle avoidance. The data of these sensors are directly fed to slave MCU via UART (universally asynchronous transmitter-receiver) or via an analog pin. The system also incorporates a closed loop feedback system via a force sensor which we measure and estimated the limits to which it can sustain load and work with efficiency. In case the load exceeds the limit that can be handled by one bot, two of them work in unison to complete the task. For barcode scanning purposes we have used a camera which feeds to the single board computer (raspberry pi) and the processed information is relayed onto the slave MCU through SPI, i2c or UART communication. If the system goes haywire we have a manually controlled kill switch which when pressed will disable the battery source.

5. Robot Specifications:
1. Maximum dimension: 550 mm x 550 mm x 300 mm (L, W, H)
2. Gross weight: 15 kg
3. Weight carrying capacity: 50 kg
4. Maximum height at open position: 400 mm
5. Number of drive wheels: 2
6. Number of castor wheels: 4
7. Max speed without load: 0.8 m/s
8. Max speed with load: 0.5 m/s

6. Conclusion
This study aims to Design and analyse a mobile robot for a storage and retrieval system. Instead of transporting individual components from a storage rack, the function of the robot is to transport the whole rack itself. The study begins with an introduction to this research and then moves on to the design aspects of the robot. To start things off, a detailed description of the design of the chassis is reported and its various design aspects and specification are mentioned. Moving on, the drive, the lifting mechanism and their respective designs are discussed thoroughly and their various functions are described. The electronic systems and components are designed and integrated to power the robot. Finally, a detailed mechanical analysis is performed on the robot via the ANSYS software, wherein a load of 550N was applied on the robot, to simulate the weight of the storage rack. The results of the analysis are discussed and their implications on the performance of the robot are studied, which help in assessing the performance and efficiency of the robot with respect to it's aim.

7. References

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