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Research on Optimization, Dynamics and Stability of Stair-climbing Wheelchair

Shashank Shekhar Sahoo*, Himank Kinkar**
*(Department of Powertrain, Magneti Marelli India Pvt. Ltd., Gurgaon-51
** (Department of Powertrain, Magneti Marelli India Pvt. Ltd., Gurgaon-51

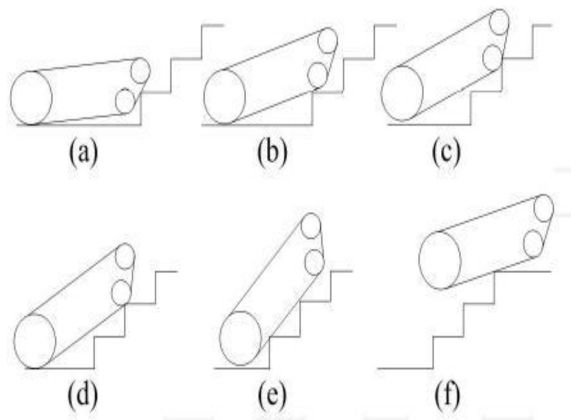
ABSTRACT
Since the invention of the wheel, man has always sought to reduce effort to get things done easily. Ultimately, it has resulted in the invention of the Robot, an Engineering Marvel. Up until now, the major factor that hampers widespread usage of robots is locomotion and maneuverability. They are not fit enough to conform even to the most commonplace terrain such as stairs. To overcome this, we are proposing a stair climbing wheelchair robot that looks a lot like a normal wheelchair but with additional stair-climbing functionality to adjust itself according to the height of the step The primarily goal of the prescribed manuscript herewith is to analyze the functional requirements, optimization methods, dynamics and stability during a tracked robotic wheelchair's climbing of stairs mechanism. At first, the mechanical structure of the wheelchair is designed and the hardware composition of its full control system is devised. Secondly, based on the analysis of its stairs-climbing process, the dynamical model of stairs-climbing is established by using the classical mechanics method. Next, through simulation and experiments, the effectiveness of the dynamical model, its stability evaluation and performance parameters is verified. Such procedures will help in establishing a strong fundamental foundation steps to design and develop a standalone semi-autonomous wheelchair that will help and enable a physically challenged person by leg to climb difficult terrains like staircase and speed-breakers with ease and comfort. This design encompasses Renesas's Arduino compatible GR-KAEDE boards, servo motors, high torque DC motors and various peripheral devices as incorporated in design diagram. We have also extended the application of wheelchair by integrating collision avoidance mechanism.
Keywords - Robot, Arduino, Climbing Robot, wheelchair, GR-KAEDE boards

I. INTRODUCTION

Modern wheelchairs are available with various accessories, such as anti-tip bars or wheels, safety belts, adjustable backrests, tilt and/or recline features, extra support for limbs or neck, mounts or carrying devices for crutches, walkers or oxygen tanks, drink holders, and clothing protectors [1]. Transport wheelchairs are usually light, folding chairs with four small wheels. These allow for a broader spectrum of movement. However, very few have experimented to enable a wheelchair with stair-climbing maneuverability.

During stairs-climbing, the wheelchair begins by touching the first step of the stairs through its front track while its two-sided driving motors simultaneously push the driving wheels and the whole wheelchair forward, up to the first step and then the second step, whereby the entire robot leaves the ground and completely climbs upwards on the stairs. The whole process may be divided into six stages, as shown in Figure 1: a) touch the first step; b) climb up the first step; c) touch the second step; d) climb up the second step; e) leave the ground and then ascend the stairs; (f) leave the stairs and then access the ground. Here, touching the step means the track near the robot's front approach angle climbing onto the step, while climbing up the step means the bottom track of the robot climbing onto the step [2].

Fig. 1



1.1 PROBLEM STATEMENT

The challenges involved in achieving the objective have been classified into the following problem statements to conquer the design in step by step approach mode.

a. To come up with a strong and robust body design upon which the entire system can rest firmly. Also, to custom-make the entire drive-train mechanism needed to automatically propel the wheelchair as per user instruction.

b. To install a set of fore-limbs(a pair of free wheels in our case) in the direction of stair climbing which will assist in traversing the first and subsequent steps with smoothness.

c. To attach a self-adjustable seating platform , that will automatically try to adjust the center of mass of whole system(wheelchair) as it ascend up the slope. It will do so with the help of gravity sensor and powerful servo motor installed in the system hardware. It can be visualized as a position control application.

d. To analyze the dynamics and stability of wheelchair in both normal surface as well as in inclined planes (stairs.)

e. To implement the collision avoidance mechanism using ultrasonic sensors and DPDT switches for controlling various operation modes of the system.

1.2 SYSTEM COMPONENTS

Our prototype design of a customized wheel-chair consists of various mechanical and electronic components that are described as follows :

1.2.1 GR-KAEDE CONTROLLER BOARD

Inputs, Processing & Output

It will receive directional instructions from the driver of wheelchair via joystick and surrounding environmental parameters(minimum distance to objects) from ultrasonic transceivers.

The **GR-KAEDE Controller** will process these inputs and will perform the following operations:-

a. Direction of rotation of DC geared motors connected to wheels.
b. Driving the servos to balance the sitting platform for maintaining it horizontal with respect to ground for providing ease, comfort and stability to the driver.
c. Detection of nearby objects probable to cause collision within a distance range preset and configured in the ultrasonic sensors. Upon detection, a status LED will glow to warn the driver. After getting the warning, there will be two drive-modes set through a switch provided to the user as follows :

Mode 0(default): The wheelchair will automatically stop until it receives mode change request from user by changing the switch to Mode 1 .

Mode 1: To continue driving as per user's directional instruction as sometimes one may want to continue to move keeping the minimum distance to object in mind.

1.2.2 GRIPPED CONVEYER BELTS WHEELS

The second most important component of our design is the wheels. The wheels will be grouped using a pair of conveyer belts. The conveyer belt will be having grips to provide friction force and traction force will be generated by the motors driving the wheels. This combination of mechanics will empower the chair to traverse and uphold the inclined plane with ease. A pair of wheels is projected few inches higher than the rest to assist in the climbing of stairs.

1.2.3 POWERFUL SERVO MOTORS

These motors will be responsible for adjusting the center of gravity of whole system by maintaining the platform horizontal with respect to ground. All servo motors, regardless of brand or type consists of four main parts.

The Mechanics : These are the drive gears and the servo case.
The Motor : This provides the motive force to drive the output arm.
The Feedback pot : This allows the servo to measure the actual position of the output arm.

The Amplifier : This is the electronics that hook all the other bits together to make it work .
The servo motor can be moved to any desired angular position by sending PWM (Pulse Width Modulation) signal on the control wire. The servo understands the language of pulse. A pulse of width varying from 1ms to 2ms in a repeated time frame is sent to the servo for around 50 times in a second. The width of the pulse determines the angular position.
A pulse of 1ms moves the servo towards 0°, while a 2ms wide pulse would take it to 180°. The pulse width for in between angular position can be interpolated accordingly. A sequence of such

pulses (50 in one second) is required to be passed to the servo to sustain a particular angular position. When the servo receives a pulse, it can retain the corresponding angular position for next 20ms, So, a pulse in every 20ms time frame must be fed to the servo.

1.2.4 3-Axis Linear Accelerometer

It will closely monitor the tilt of sitting platform with respect to ground and will assist in maintaining a perfect horizontal level as required to keep the integrity of comfort and stability. The ADXL335 is a small, thin, low power, complete 3-axis accelerometer with signal conditioned voltage outputs. The product measures acceleration with a minimum full-scale range of ±3 g. It can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion, shock, or vibration.

1.2.5 Power Source

A single 12V rechargeable DC battery to supply enough current to drive huge inductive loads of high torque motors and related accessories.

1.2.6 Collision avoidance sensor (UV transceivers)

The sensors will check, detect and inform the microcontroller about any imminent collision possible due to any nearby object. The HC-SR04 ultrasonic sensor uses sonar to determine distance to an object like bats or dolphins do. It offers excellent non-contact range detection with high accuracy and stable readings in an easy-to-use package. From 2cm to 400 cm or 1" to 13 feet. It's operation is not affected by sunlight or black material like Sharp rangefinders are (although acoustically soft materials like cloth can be difficult to detect). It comes complete with ultrasonic transmitter and receiver module.

1.2.7 Joy-stick

To accept directional instructions from the user. The 2-Axis Joystick is used to add analog input to our project. The 2-Axis Joystick contains two independent potentiometers (one per axis) that can be used as dual adjustable voltage dividers, providing 2-Axis analog input in a control stick form. The modular form-factor allows one to plug the 2-Axis Joystick directly into a breadboard for easy prototyping. The 2-Axis Joystick includes spring auto return to center and a comfortable cup-type knob which gives the feel of a thumb-stick.

1.2.8 Geared DC Motors

To drive the wheels interlocked with conveyer belts. These are very high torque powerful motors with the capability to drive the entire system with ease and activates upon receiving user input from joystick.

Other active and passive electronic components like resistors, LEDs, transistors etc.

II. WORKING PRINCIPLE

The customized wheelchair will take directional instructions as input from driver and will drive the wheels accordingly as per processed logic. In the event of staircase climbing, the driver has to orient the wheelchair with backside facing the stairs. Then continue normal traversing until the first step is covered [2]. In order to maintain stability, the servo motors will then align the sitting platform horizontal to ground by rotating through an angle alpha(α). While undertaking this process, 3 axis-Accelerometer will continuously monitor the level change of platform with respect to gravity and will help in achieving accuracy and stability. With this configuration, one can climb the further steps with ease. When the distance to potential colliding object measured by ultrasonic sensors violate the threshold preset conditions, an alert will be displayed on LCD to stop the wheelchair automatically as per **Mode 0** operation and will wait for next user's instruction to switch into **Mode 1** to continue moving , keeping minimum distance to detected object in mind.

III. System Design Specification

3.1 MECHANICAL

The chassis used in the wheelchair is an in-house custom-made prototype that involves the combination of an innovative axles, highly stable metal body, bi-cycle sprocket with gear sets and screw joints to fix them all together. The axles used in the project are actually reverse-engineered version of what we normally see in bicycle, where a single pedal turn of larger diameter sprocket results in multiple turns of smaller diameter sprocket connected to the rear wheels. Similarly, here also we have mechanically coupled a pair of wheels with similar axles and installed gear set on it which will be propelled by high torque powerful DC motors using driver and driven mechanism. The sprocket of front and rear axles are coupled mechanically using chain- links that are usually found in bi-cycles, and these are customized and adjusted to fit the design with zero tension and torsion force. This mechanism is replicated on other side as well taking into account the other pair of wheels. The USP of this particular design is that just by connecting a single high torque DC motor, one can propel the entire one-half of the system. So, technically speaking two motors are sufficient enough in this design to propel the entire four-wheel drive system with ease and comfort. Four such combination consisting of sprocket, axle, axle with gears and chains are formulated in such a manner to provide high stability to the system [3].

Custom made special slots are provided in the proximity of two axles to hold the DC motors in place. The motor shafts are fitted with gear of smaller number of teeth and it is linked mechanically with another gear of larger diameter to multiply the torque received at the wheel end to drive the system. A good schematic of the custom design along with its part is given as follows.

Fig. 2

Fig. 3

Fig. 4

3.2 ELECTRICAL

The major challenge faced during the design of system electrically is to comply with required and rated value of voltage and current in the entire circuitry as it involved the usage of huge-current hungry loads(sinks). We often encountered problems of sudden voltage surge and current drop and sometimes vice –versa as well while testing the system under both actual resistive and inductive loads . This was handled to the best possible extent by using calibratable motor drivers and adjustable power adapters to sync the movement electric parts with that of mechanical ones. Also, selecting a perfect motor to drive the wheelchairs with accurate torque and rpm rating was also not easy. We have to check it with multiple combination and have selected one that can sustain the bulky system not only on level-ground but also on inclined planes of stairs.

3.3 ELECTRONICS

Electronically, we have interfaced multiple sensors such as ultrasonic sensor, accelerometer, joystick and peripheral modules such 16x2 LCD, that are driven by 5V supply from GR-KAEDE board itself. So, interfacing all of them together without inducing delay and without compromising with the processing capability of the 32-bit Renesas controller was difficult to handle from software end. We tried to develop software of our system via modular development strategy to the best possible extent. However, due to the constraints of the IDE and Renesas web compiler, we couldn't consolidate the code . The number of code lines could have been reduced if the entire module of all parts can be developed separately and deployed independently of each other. We have followed here a step by step strategy to focus on single interfacing of sensors and peripherals at a time and then integrated them all together to build the system. Doing such also helped us in debugging the system better in case of any malfunction. Also, separate power supplies of 5V and 12V are handled in isolation without any interference.

IV. GRAPHICAL DIAGRAM

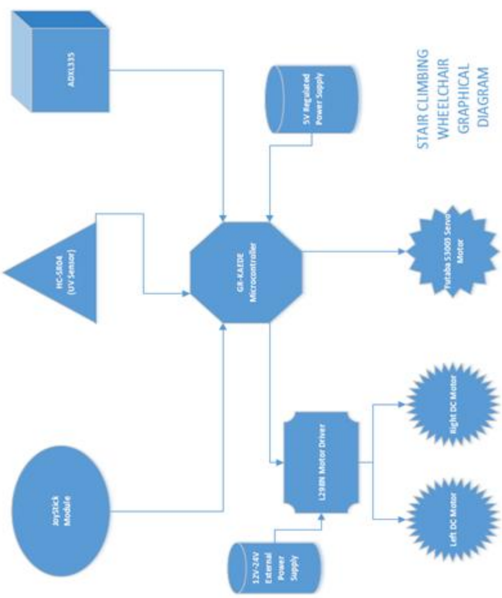


Fig. 5

IV. IMPLEMENTATION NOTE

It started with chassis design which is a rectangular frame with compartments for wheel and driving motors. Then the axle design, that has been customized out of bi-cycle axles. It has been made retro fit to accommodate gears and sprocket around the opposite sides of rim. Four such units were designed with sprockets on all the four and driving gears on the rear wheels [4].

We needed to add additional pair of wheels to enable the wheelchair to climb the stairs . For this a separate pair of wheels were made to project out of wheelchair body with marginal lift but in alignment with other wheels. The main usage was to assist the wheelchair to climb stair steps with ease. The next step was to wrap around a set of two conveyer belts encompassing wheels in phase and alignment. Doing such made the wheel drive more robust and it ensured proper movement of wheels in difficult terrains without losing traction and control off the road or stairs.

Later on, a stable light weight platform was attached around the horn of the servo and was mounted with the help of two center mast from the central section of chassis. This platform is also connected mechanically to accelerometer to detect change in orientation of the platform and to make the platform parallel to the ground.

As add-on in our custom designed wheelchair we have also attached an ultrasonic sensor in the façade of system to detect any nearby object which might cause imminent collision.

During prototype testing it was observed that the sprocket chain arrangement was creating a hurdle while climbing the stairs as the radius of the wheels chosen wasn't providing sufficient edge clearance. So, chain was removed.

All these modules were tested within their constraints and in compliance with their specification to meet the required objective over various load conditions.

V. CIRCUIT DIAGRAM

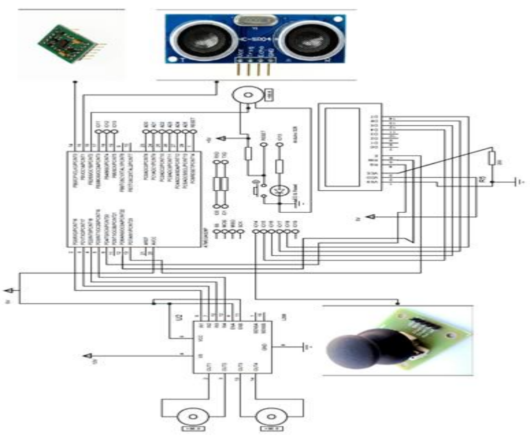


Fig. 6

VI. SYSTEM TESTING, RESULTS & DISCUSSION

The wheelchair system is developed in compliance with modular development strategy. So, it's testing is also done in somewhat similar manner. We have performed multiple unit – testing of various system parts while they are under development in order to ensure about the quality, endurance, stability , robustness and integrity. Some of the tests performed are as follows :-

a. Test to check proper fitting of wheel cut-set with that of axle.
b. Test to inhibit back free-movement of sprocket by welding of sprocket inner body with that of axle.
c. Test to check and ascertain any relative motion between gear cut-set and axle , that might result as consequence of loose bond between the two parties.
d. Test to ensure ground clearance and stability of entire system while the installation of all four wheels is done.
e. Test to observe the behavior of system in terms of traction control, stability, driving torque and custom manoeuvrability by just installing the motors but not the conveyer belts. Technically, we want to make it traverse an inclined plane simulating the same angle of inclination as that of stairs.
f. Next test was to fit the chain-links encompassing both front and back sprocket with no tension and with perfect ground and stair clearance.
g. Test to check whether the wheelchair is able to climb the very first step or not after fitting the conveyer belts in their place.

For the purpose of proving the results of the dynamical model and the stability analysis for stairs-climbing, we perform a simulation calculation and experiments on the developed wheelchair robot. The structural parameters of the robot are: the radius of the driving wheels is R=250mm; the radius of the steering wheels and the fixed wheels are both r=140mm; the length of the bottom tracks is L=600mm; the front approach angle is α=40°. The robot has two DC servo motors with 400 watts power and the total mass of the robot is m=62kg. The frictional factor between the tracks and the sharp corner of the steps is 0.2.

According to the defined modes of motion, we make a simulation calculation of the wheelchair's stairs-climbing experiments . In Figure 7, the stability profile of wheelchair during the course of its manoeuvre are best depicted in the profile below :-

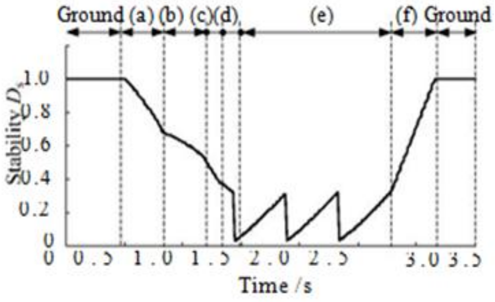


Fig.7

The lowest point of stability during the robot's stairs-climbing occurs during those moments when the driving wheels leave the ground and the robot's driving wheels roll over the first and second steps. The main reason is that the driving wheels are suddenly suspended in the air. This has the result that the robot's rolling fulcrum moves forward substantially and thus it inclines to tumble backwards more easily. This conclusion is also proven in the tracked mobile robot's stairs-climbing experiments [5].

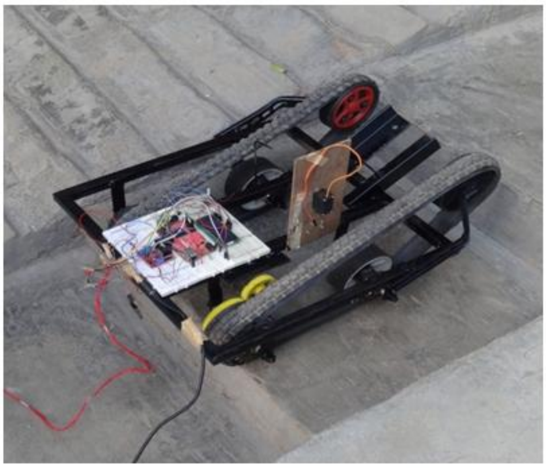


Fig. 8

The stability conditions for its stairs-climbing are obtained. A quantitative evaluation method of the stairs-climbing stability of the tracked mobile robot is proposed and verified through simulation and experiments.

This project will solve the issues faced by physically challenged person through leg in day to day life such as climbing staircase and having additional security by averting collisions. This project can be further extended to incorporate feature like android application or wireless technology based emergency message alert and providing directional input to wheelchairs via icons displayed in the smartphone screen. The emergency notification will inform the relatives instantaneously, thus providing safety and security to the rider. This design can be used to carry heavy objects in multistory buildings and military surveillance purposes. It has the potential to play active role in disaster management situations also.

VII. CONCLUSION

Given a wheelchair the issue of how to ensure stability in stairs-climbing is an important problem which needed to be solved. Looking at this problem, the dynamical model and the question of stability during wheelchair's stairs-climbing are studied based on a mechanics analysis. The acquired achievements can provide design and analysis foundations for the wheelchair' stairs-climbing and solve the problem, which can be summarized as follows:

(1) According to the requirement for stairs-climbing, the mechanical structure of a tracked mobile robot is designed and the hardware composition of its control system is given.
(2) Based on the analysis of the stairs-climbing process, the dynamics model of the tracked mobile robot during stairs-climbing is established, which can provide fundamental support for the stability analysis.

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