Design and Analysis of Building Diagnostics Robot

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Abstract. This research paper is based on the designing and analysis of a track-based robot which has the capability of climbing stairs and rough terrain maneuverability with an IR sensor to conduct infrared thermography of buildings. The data generated by this can be used to detect and optimize HVAC systems, moisture damage and Electrical issues. The robot is designed in Solidworks software and motion analysis is done using Adams and structural analysis through Ansys. The Thermal imaging camera was tested in the real world to check the feasibility and accuracy of Infrared Thermography.

Keywords - Infrared Thermography, HVAC Systems, Track based Robot.

1. Introduction
Infrared thermography is a method of detecting infrared radiations emitting from an object and converting it into temperature and then the temperature distribution is displayed. With the help of infrared thermography temperature distribution of the surface can be changed to visible data. It is a good method of real time temperature measurement without any physical contact with the surface.

In 1800 the infrared radiation was discovered by William Herschel and after the discovery of thermoelectric effect in 1821 by Thomas Seeback. Scientists have measured radiation with the help of thermopiles and thermocouples [1,2].

Thermography is based on object emissions, but three basic radiation laws coincide with the practical concept of IR thermography:
1. Kirchhoff’s law of thermal radiation, establishes the relation between emission and absorption of energy, indicating that a body which absorbs much also emits much and, according to this principle, the emission coefficient, ε, is introduced in equation as the ratio of emissivity, E, of a real body to the emissivity, Es, of the black body under the same temperature ε = E / Es. The emission coefficient, ε, is non-dimensional and takes values between 0 and 1 and depends on wavelength, on temperature and the surface texture of the body.

2. Planck’s law of radiation describes the specific spectral radiation I’ emanating from the idealized blackbody.1) If the specific spectral radiation, I, is plotted over the wavelength, λ, as a function of temperature, typical Planck curves will result. it can be seen that the maximum of the curves shifts with growing temperature towards a smaller wavelength according to the Wien displacement law, λ = b/T,
where $T$ is the absolute temperature of the black body, $\lambda$ is the peak wavelength, and $b$ is a constant of proportionality called Wien’s displacement constant equal to $2.897771955 \times 10^{-3}$ m·K

3. Stefan–Boltzmann law, applied to the emission of a surface over all wavelengths, integrated the Planck law and discovered that the radiant power, $I$, [W/m$^2$], grows with the fourth power of the temperature, $I = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8}$ W/m$^2$K$^4$. [1,2]

Infrared thermography is attaining a lot of traction in the fields of aviation, medicine, research etc. because of their development and usability. Infrared thermography is also used for the strength assessment of concrete surfaces. Concrete surface quality is determined by analyzing the infrared camera images and the measurement data obtained. In the case of large concrete structures, mobile robot equipped with high quality measuring devices are used. The mobile robot requires the use of a microprocessor control device that carries out measurements independently, collects measurement data and send it to the master unit [3]. Infrared thermography is an acceptable method of conducting non-destructive testing of building materials, heat energy distribution in a building, and can be used in the heat, ventilation and air-conditioning installations. The information collected can be used to identify potential concerns, measure potential energy savings, plan preventive maintenance measures and minimize the likelihood of failure [1].

2. Methodology

2.1. Design

The first design objective is to build a robot capable of moving in the area of construction sites without any obstruction. Construction sites consist of gravels and uneven surfaces. Our model consists of mechanisms to move across uneven terrains such as suspension systems, wheels with high traction, wheels that can rotate along two different axes and tracked wheels. The Robot uses tracked wheel system to achieve this objective. This design approach provides more stability to the robot to handle any terrains, and it has already found applications in military-grade units such as tanks. This design also has more advantages when it comes to simplicity of design and servicing the robot. The authors chose a double-sided timing belt system for the tracked wheel design where a belt connects to a pair of Trapezoidal toothed pulley. It is designed with a T10 tooth profile. The thickness of the belt is 2mm.

The second design objective is to make the system able to ascend stairs of constructed buildings. Many mechanisms are available to achieve this objective. Some robots have leg-like structures, movable multi-wheel designs, and movable flipper-like mechanisms. The robot uses a flipper mechanism to achieve this objective. There are two pairs of the track system in this robot. One set of the track system is connected to the chassis, and the other set of the track system connects to the flipper arm.

The flipper arm connects to the chassis through the shaft. The shaft passes through all four front wheels and supports of the robot. This design makes sure that the flipper arm can rotate freely without affecting both sets of the track system. To control the angular displacement of the flipper, the shaft component needs to be rotated accordingly. To achieve this, a worm drive mechanism is implemented. This worm drive mechanism consists of two components worm gear and spur gear. The worm gear is attached to an electric motor, and the spur gear is fixed to the shaft of the flipper component. The ratio of rotation between the worm gear and spur gear is 18.62, i.e., for 360-degree rotation of worm gear, spur gear moves 19.33 degrees in angle. This way, flipper arms can be precisely move with an electric motor. In order to decide the length of flipper arm, the center distance between pulley wheels, maximum height, and width of the stair needs to be determined.

Maximum height of the Indian stair = 200mm
Maximum width of Indian stair = 360mm
While the robot ascends stairs, it will be in a slant position such that the contact between the robot and stairs is minimum at four places and maximum at six places. The center distance between the pulley wheels is chosen as the hypotenuse of the right-angled triangle formed by the stair's height, width, and slant.

$$\text{Centre distance between pulley} = \sqrt{(\text{Height of Indian stair})^2 + (\text{Width of Indian stair})^2}$$  \hspace{1cm} (1)

$$\text{Centre distance between pulley} = \sqrt{(200)^2 + (360)^2}$$  \hspace{1cm} (2)

$$\text{Centre distance between pulley} = 420\text{mm}$$

With tiny allowances, the length of the robot chassis was determined as 550mm. The set of tracks connected to the chassis drives the rear pulley wheels for the robot to move. Both rear wheels are connected to separate electric motors to achieve steering of the robot by rotating both motors at different rpm. The robot has an upper basement independent of the chassis. this upper basement contains a visual camera and thermal camera. this upper base is connected to the lower basement through an electric motor so that camera can get a full 360° view.

2.2. Control Design
For controlling the robot, the micro-controller used is Raspberry Pi 4. It is connected to 4 electric motors, a thermal camera, and a visual camera. The two motors are connected to rear wheels, one servo motor for rotating flipper arm and the other for rotating the upper basement of the chassis. These motors are connected to the micro-controller through the motor driver to boost the speed using a battery. The 5v separate battery is used for raspberry pi, and the 12v battery is connected to the motor driver to run the motors. The robot is controlled through a laptop. The laptop can be connected to the Raspberry pi through an inbuilt Wi-Fi interface and can control and view the images via SSH and VNC connection.

2.3. Mechanical Design
The robot has dimension (55 × 45 × 28) cm which is the length, width and height respectively. See Figure 1.

**Figure 1.** Basic Dimensions of robot
The stair climbing robot is capable of moving in uneven terrains and to easily maneuver urban environment, climbing stairs and also do the thermal analysis. It will carry IR module, which consists of an infrared camera and a normal camera where both of their focus is set to the same location in space. So, both the infrared image of the place and the digital image can be used to navigate the bot remotely. See Figure 2 and Figure 3.

Figure 2. Top view of the robot

Figure 3. Isometric view of the module

3. Materials and Components
The robot is track-tread based and with actual flippers that can aid in climbing the stairs. The flippers have independent track with wheels at the end of the flipper. Flippers will provide higher stability in slopes, and better mobility along stairs and have high power efficiency [4]. The authors have used four motors, out of which three are used for robotic motion and one is used for positioning the thermal camera.
For robotic motion flippers are actuated using a worm gear connected to a motor and the other two motors are used for track mobility.

Aluminum alloy A1050A T3 was selected to make the rover chassis. Since, it possesses good strength to weight ratio, is easily machinable, better yield strength, tensile strength and Poisson’s ratio of 0.34. Chassis part can be welded using TIG welding [4,5]. See Table 1.

### Table 1. Properties of Al AA1050A T3

| Alloy     | Temper | Proof stress 0.20% (MPa) | Tensile strength (MPa) | Shear strength (MPa) | % Elongation (A5) | Brinell hardness (HB) | Fatigue endurance limit (MPa) |
|-----------|--------|--------------------------|------------------------|----------------------|-------------------|-----------------------|-------------------------------|
| AA1050A   | T3     | 290                      | 365                    | 220                  | 15                | 95                    | 250                           |

3.1. Treaded Tracks

The shape and size of treaded tracks will greatly affect the efficiency of the rover [4]. The treaded track should have enough grip to hold the rover from slipping, should have good adhesion characteristics and should be cost effective. Hence fixed geometry tracks were selected and these tracks transmit the force to the ground from the driven sprockets. Reinforced synthetic rubber with chevron tread was used for the tracks. Since it is lighter, produce less noise, impose more ground pressure below the wheels, and gives good surface traction.

The major properties of reinforced synthetic (SBR) rubber are good temperature range (-60°F - +220°F), high durability, high tensile strength, high abrasion resistance, excellent tear resistance, good vibration dampening and good resilience [6,7].

3.2. Worm Gear for Flipper Mechanism

Worm drive was selected for the transmission of power between the flipper motor and the flipper axle, from different mechanisms like belt, chain, spur gear, etc. because of their self-locking capability and compactness.

**Motor and battery selection**

- Required torque, power calculations:
- Rover mass, \( M = 3 \text{kg} \)
- Wheel diameter: \( D = 70 \text{mm} \)
- Nominal speed required, \( V_n = 0.3 \text{ m/s} \)
- Acceleration time required, \( T_a = 0.5 \text{ s} \)
  
  \[
  \text{Wheel rotation speed, } N_t = \frac{60 \times V_n}{\pi \times D} = 81.85 \text{ rpm} \tag{3}
  \]

  \[
  \text{Force, } F_t = M \times a = 3 \times 9.81 = 29.43 \text{N} \tag{4}
  \]

  \[
  \text{Power, } P = F \times V_n = 8.83 \text{ W} \tag{5}
  \]

  \[
  \text{Torque, } T_t = F \frac{D}{2} = 1.03 \text{ Nm} \tag{6}
  \]
• Power for 1 wheel = 4.42 W
• For 1 wheel, torque = 0.52 Nm

While considering coefficient of friction, total torque required can be calculated by,

\[ M_{total} = MF + MB = FF \times R + FB \times R = \frac{\mu m g R}{1 + \mu^2} + \frac{\mu^2 m g}{1 + \mu^2} = \frac{\mu (1 + \mu)}{1 + \mu^2} m g R \]  

(7)

Were, MF – Torque at front wheel
MB – Torque at back wheel
R - Radius of the wheel = 35mm
Coefficient of friction, \( \mu = 1.8 \)
i.e.; Total torque required = 1.6 N-m
Torque required for each wheel = 0.8 N-m

Therefore, for a 12V motor it should have 0.6 amps to get required torque for one wheel. Two 12V brushless dc motor is used for track mobility. The selected N20 Micro Gear 100RPM DC Motor’s specifications are:

• Rated Voltage Current: DC 12V, No Load Current: 0.06Amps (Max 0.75 Amps)
• No load Power Consumption: 0.72 Watts (Max ~9 Watts)
• No Load Speed: 100RPM

To enable 360° rotation of the flipper it is required to use a dc motor instead of servo motor, while considering the torque required and the frictional losses between the gears it is better to use a dc brushless motor having 0.6Nm torque. Therefore, N20 Micro Gear 100RPM DC Motor is selected and one servo motor is used for sensor positioning (TowerPro Sg90-1.8 kg-cm).

3.3. Electrical And Electronic Components
1) N20 Micro Gear 100RPM DC Motor - 3
2) Servo motor MG 995 - 1
3) Motor controller – L298 - 2
4) Battery – 12V, 10000 mAh Li-ion
5) Raspberry Pi 4
6) Thermal imaging camera – seedstudio MLX90641

The IR thermal camera carries a 16 x 12 array of thermal sensors and it can detect the temperature of objects from far away with a center area accuracy of ±1°C and an average accuracy of ± 1.5°C.

4. Motion Analysis
The biggest hurdle in an urban environment is stairs, which humans can easily navigate. But for a robot, it needs an external mechanism to climb stairs. This robot uses Flipper mechanism driven by a combination of worm and spur gears to get the desired motion. The next step was to test the robot in virtual environment. The robot was designed using Solidworks and then tested using MSC Adams Software, where real life conditions can be simulated. See Figure 4.

For the test case, the test environment was created with an uneven ramp and a stair flight of 5 stairs. The uneven ramp is to detect whether the robot can move in uneven surfaces. In India there are wide variety of stairs, ranging from small to large ones, but one-meter-wide stairs with 200mm riser height and
360mm going length was chosen, with a hypotenuse of 420mm. This is an extreme case; so, if the robot is able to climb this, then it can climb all the other stairs constructed in India [8-12].

**Objective:**
- Find the torque required to lift the robot and climb the stairs
- Tension in the tracks to avoid the contact between stair and chassis
- Stability of the robot while climbing
- Average velocity of robot during the whole process

The parameters considered are:
- Angular velocity of the wheels attached to the motor, Step function for the flipper mechanism to activate at specific time period, Material for robot chassis components, length of track belt to adjust stress and strain of the track. Properties that were assumed:
  - The belt is continuous
  - No heat is generated during contact
  - Worm Drive is highly efficient
  - Belt is highly flexible

The assumed design variables:
- Dynamic Friction Coefficient value = 0.8 (Rubber - Concrete)
- Static Friction Coefficient value = 1
- Penetration depth (for all contact forces) = 0.1mm
- Driving wheel speed = 60 RPM

4.1. The Different Stages:

Full stair climbing process occurs in 4 stages:
- **Stage 1:** Reaching the Stairs
  - The robot climbs the ramp and reaches near the first stair. Now it activates the worm drive motor, so that the flipper turns and gets into contact with the stair. The slope of the stair is $29^\circ$ and it rotates the flippers to this angle. See Figure 5[a]
- **Stage 2:** Activating the flipper and starting to climb the first stair
  - Now the flipper supports the whole chassis and lifts the front of the robot to the slope of the stairs. Then the driving motors are spun at high rpm for climbing the stairs. See Figure 5[b]
- **Stage 3:** Climbing the slope of the Stair
  - Now, the robot is parallel with the slope of the stair and it then climbs the stairs as if it were moving in a horizontal plane. See Figure 5[c]
- **Stage 4:** Reaching the top and retracting the flipper
  - When the robot reaches the top, then it stops and then retracts the flippers to reduce the aspect ratio of the robot. See Figure 5[d]
Figure 4. The Robot at the starting position

Figure 5. (a) Activation of the flipper. (b) Robot starting to ascend the stairs. (c) Robot climbing on the slope as if it were moving in a horizontal plane. (d) The robot at the destination, now retracting the flipper to move efficiently.
5. Results

After running multiple simulations, the following results were obtained:

- The Maximum torque generated by the driving motor to climb the stairs is around $6.2 \times 10^3$ Nm. See Figure 6.
- The Torque needed to lift the chassis is $8.75 \times 10^2$ Nm. See Figure 7.

![Figure 6. The torque produced by the driving wheel motors](image)

![Figure 7. The torque produced by the worm drive mechanism](image)

- The Tension of the belt is around 770.637 N/mm.
- The belt-system acts as a self-balancing system, i.e., it stabilizes and makes itself parallel while climbing the stairs, even if it climbs at a wrong angle.
- The Average Velocity of robot is 0.75m/s. See Figure 8.
Figure 8. The overall velocity of the robot during simulation

6. Structural Analysis
The structural analysis of base was done on Ansys software. The forces acting on these structures were obtained from motion analysis. Quadratic tetrahedrons were used for meshing along with fine meshing size to obtain accurate structural analysis. The results obtained shows deformations and von-Mises stress that are well under the acceptable range.
- The maximum von-Mises stress for base is 10.32 MPa. See Figure 9.
- The maximum deformation for base is 0.009mm. See Figure 10.

Figure 9. Von-Mises stress of the base
7. Thermal Imaging

![Thermal Imaging Images]

Figure 11. The real and thermal image of the window(a) and of the Roof(b).

The window is much hotter than the surrounding walls. This is due to poor insulation of windows and the use of single pane glass. Heat is easily conducted by the glass and there is air penetration through the edges of the window frames. See Figure 11(a).

The roof is hotter and is red coloured in the thermograph, the blue coloured area is the side walls. The roofs are exposed to the sun's radiation for maximum duration hence they get hotter than the side walls which get irradiated for a much shorter time. Here lack of insulation on the roofs leads to warmer roofs hence larger amount of energy is required for cooling the room. See Figure 11(b).

The results obtained show that infrared thermography can be used to detect thermal irregularities with good accuracy and this data can be used to optimize HVAC systems.

8. Conclusion
This paper discusses the modeling and analysis of a building diagnostics robot that uses infrared thermography techniques to measure heat dissipations, temperature variations and electrical damages. This data aids in optimizing the HVAC systems of buildings. Large variation in the temperature (Thermal irregularities) mainly indicates leakage of air, voids in the internal surfaces, the spread of moisture, water leakages, electrical circuit damages, presence of internal and external cracks, lack of insulation, etc.
The rover can be used for real-time data collection by remotely taking thermal images of the surface under examination, store the recorded data, and helps to visualize the measured data in real-time. With the help of treaded tracks, it has better mobility through rough terrains and stairs. Along with better agility and stability which helps the rover to record data efficiently. Major advantages of using infrared thermography are quick and accurate diagnostics of buildings, identifying any anomalies if present at the time of construction which will help in future works and better reliability of the building, it will reduce guess works, allows real-time consultation with experts who are offsite and thereby it helps in better interpretation of the problem and finding better solutions in a fast manner.

9. References

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