Design and Construction of an Unmanned Ground Vehicle

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Abstract

Alongside a myriad of applications, robots are widely used in hostile environment exploration, search and rescue management, surveillance and target tracking. The authors evaluate the design and construction of an unmanned ground vehicle developed on Arduino open-source platform and focus on minimizing the effects of ground induced vibrations on overall operability of such robots. Due to its complex geometry, the stiffness of the frame is evaluated and optimized by Finite Element Methods.

Keywords

Unmanned Ground Vehicle, Open Source Electronics, Ground Induced Vibrations, Finite Element Modeling, Sensor Errors.

Design Aims and Challenges of Unmanned Ground Vehicles

A combination of low cost and operational reliability is a major requirement for all unmanned ground vehicles, specifically for the ones involved in target tracking and environmental exploration. The Italian company Arduino from Turin offers the solution with its line of open-source platform of microcontrollers like Arduino Uno, available on a student budget [01]. The main components involved in the control of the robot are illustrated in figure 1.

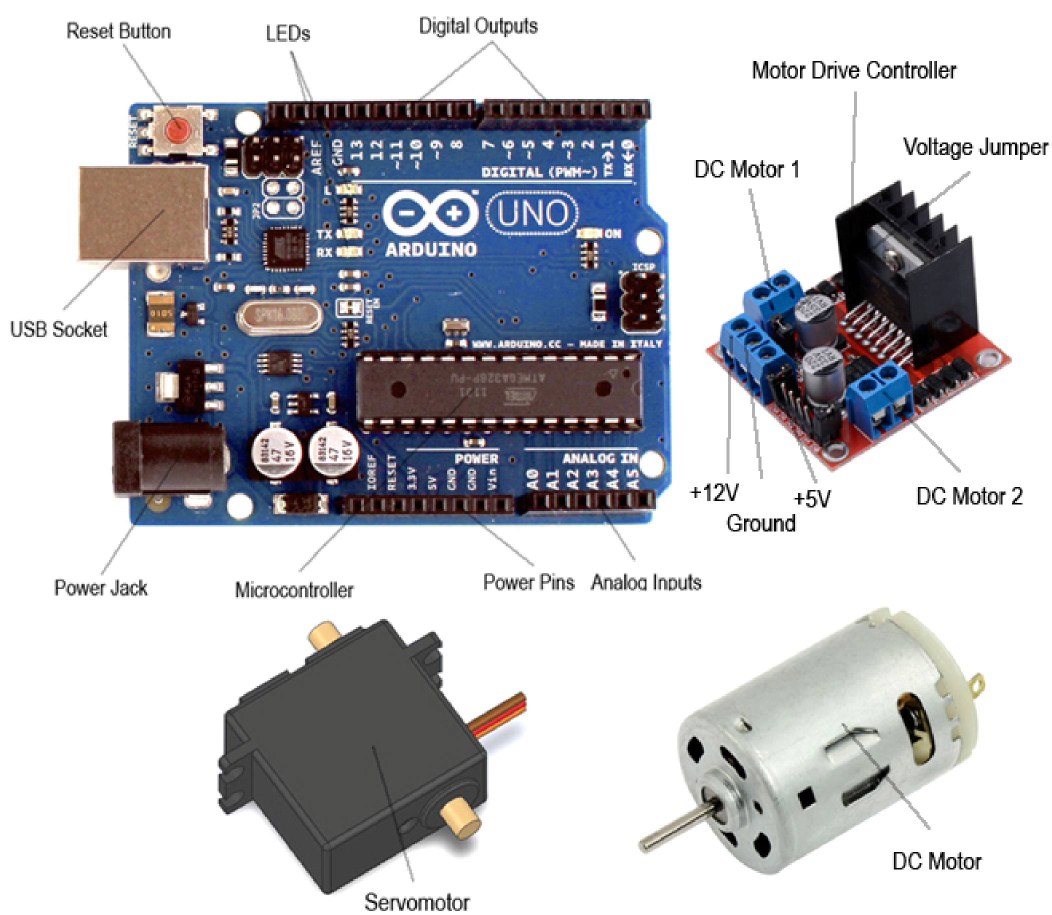


Figure 1. Arduino Uno Microcontroller, Motor Drive, DC Motor and Servomotor

Unmanned Ground Vehicles are autonomous robots and their sensors and servo systems are remotely controlled. One important challenge faced by the developers is the control of the DC Motors – the simplest electric motors used in robotics. The rotational speed of the motors can be changed by employing the Pulse Width Modulation technique, which allows the control of the average voltage delivered to them by turning the power on and off at frequency rates of the order of 10^4 Hz. The Pulse Width Modulated signal delivered by any microprocessor including Arduino Uno can be provided at the gate of a MOFSET and the rotational speed of the DC Motor will change as function of the duty cycle of the signal. Such electronic circuits are not effective in changing the direction of rotation. For these requirements there is a need of an H-Bridge circuit consisting of four switching elements like MOFSET transistors. Dedicated H-Bridge Motor Drive ICs are commercially available [02] and the L298 DC Motor Drive is employed in the development of the robot discussed in this paper. The L298N Motor Drive IC is a 15-lead high voltage, high current Motor Driver IC with two full bridge drivers. The logic levels of L298N IC are compatible with standard TTL and IC can be used to drive different inductive loads like DC Motors, Stepper Motors or Relays. The Pin Diagram, the connections to Arduino Uno microprocessor and example code written in Arduino Integrated Development Environment are illustrated in Figure 2.

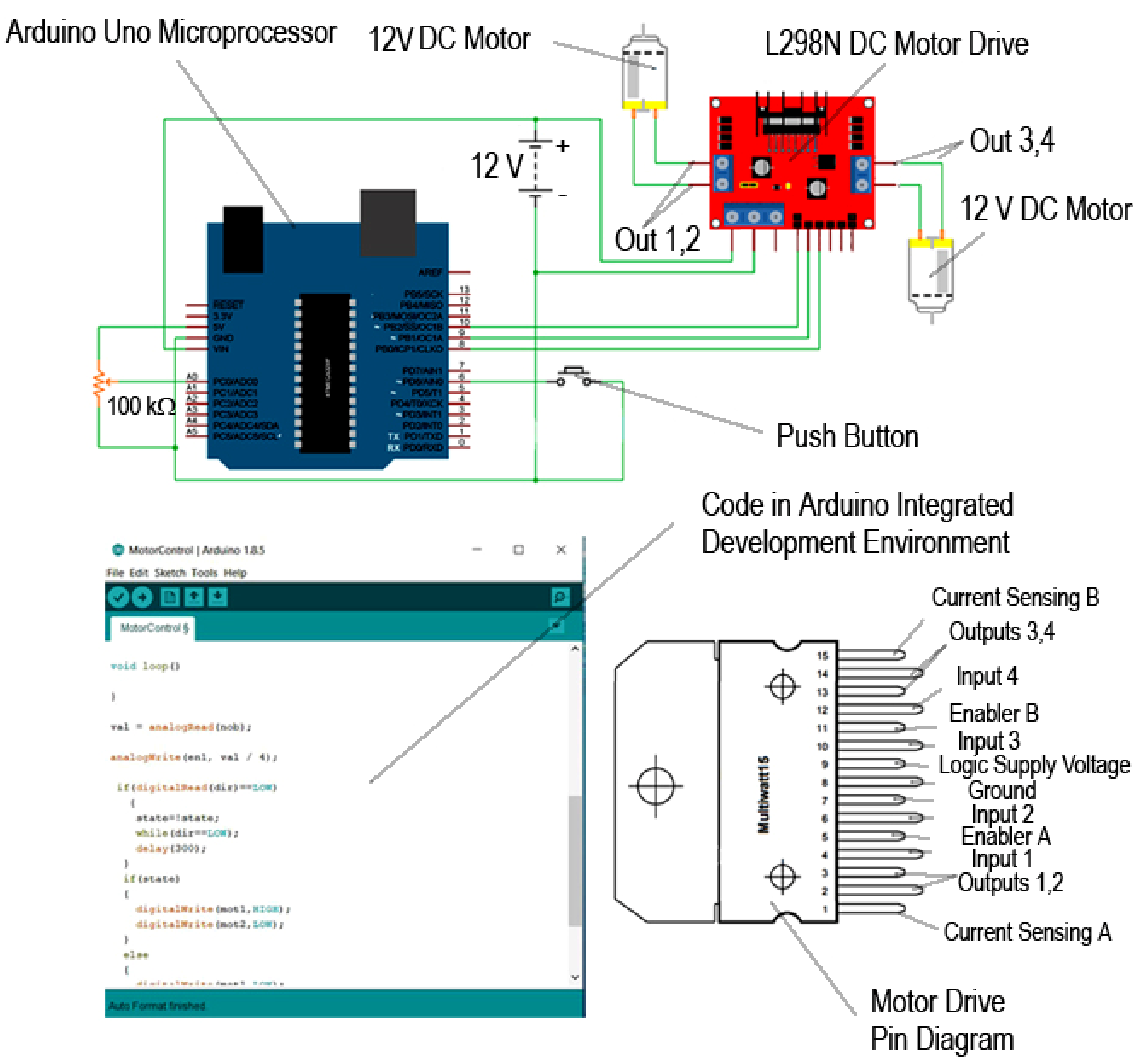


Figure 2. L298N Motor Drive connections to Arduino Uno and Example Code in Arduino IDE

Similar challenges in the development of the robot are mechatronics specific and some are discussed in this paper. The integration of both electronic and precision mechanics subsystems is related to the simplified schematic representation from Figure 3 and a 3D model of the robot designed in SolidWorks and relevant details are illustrated in figure 4.

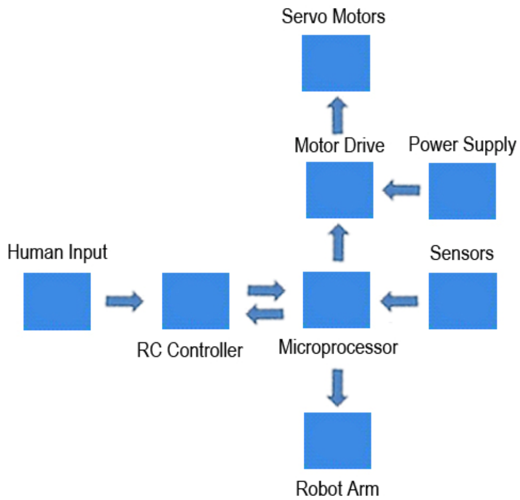


Figure 3. Schematic Representation of the Robot's Controls

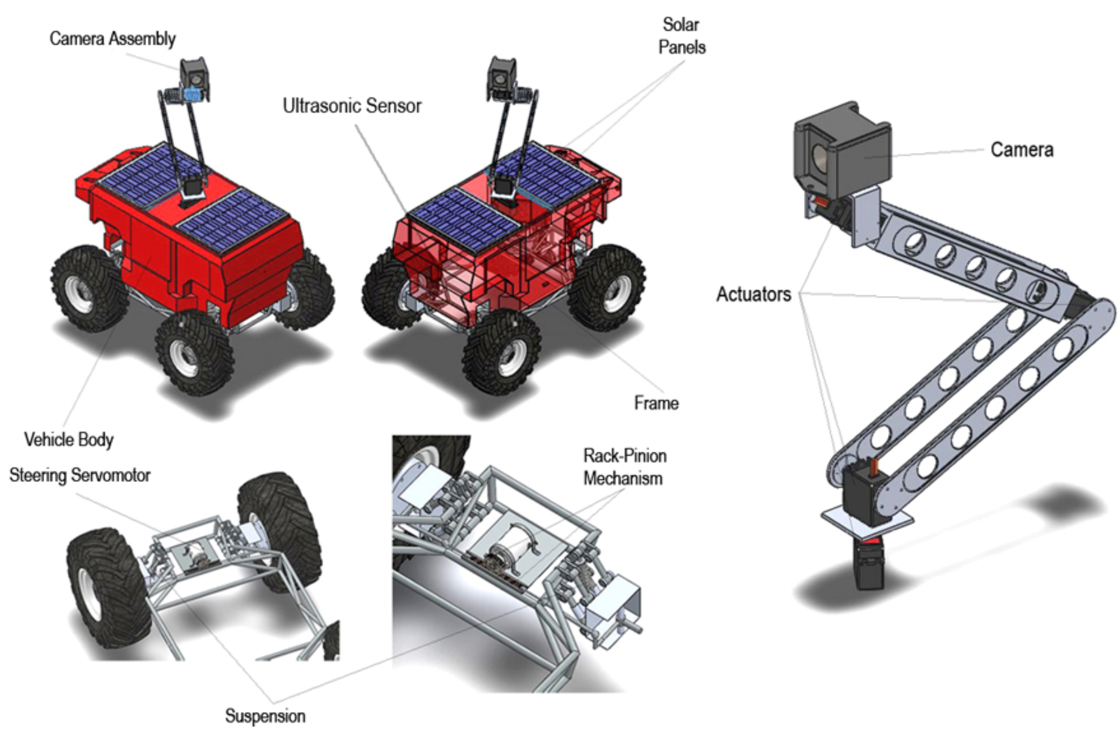


Figure 4. 3D CAD Model of Unmanned Ground Vehicle

Power Requirements

In robotics, motion planning is related to the energy consumption and task reliability. Some authors developed analysis procedures for robots powered by batteries using Matlab [03]. The analysis is mostly based on experiment, and considers the power requirements for all servo motors in service. However, the method is superficial regarding the kinematics and dynamics parameters of autonomous robots and the influence of terrain.

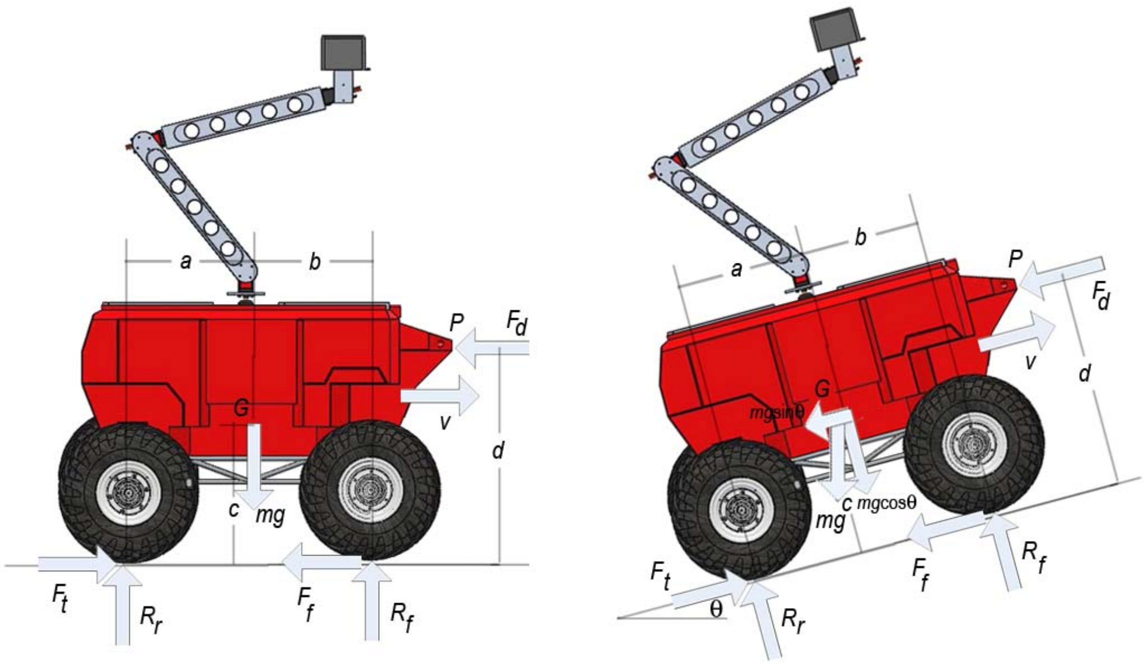


Figure 5. Schematic Representation of Dynamic Conditions on Generic Unmanned Ground Vehicle

In general terms, the power required at robot's wheels level and related to the schematic illustrated in figure 5 is defined as:

$$P_{tw} = \frac{v}{\eta} F_t \tag{01}$$

The significance of the parameters involved in equation (01) is:

- P_{tw} - Power required, expressed in W
- v - Linear velocity, expressed in m/s
- F_t - Traction force at constant linear velocity, expressed in N
- η - Overall efficiency, roughly 0.9 for direct drive systems

The traction force F_t at constant linear velocity is dependent on the slope of the ground:

$$F_t = mg\left(\mu_r \cos\theta + \sin\theta\right) + F_d \tag{02}$$

The significance of the parameters involved in equation (02) is:

- F_t - Traction force at constant linear velocity, expressed in N

- m - Mass of the robot, expressed in kg
- g - Gravitational acceleration, expressed in m/s^2
- μ_r - Rolling resistance coefficient
- F_d - Aerodynamic drag, expressed in N
- θ - Slope of the ground

On horizontal ground $\theta = 0$, $\sin\theta = 0$, $\cos\theta = 1$ and equation (02) becomes:

$$F_t = \mu_r mg + F_d \tag{03}$$

The rolling resistance coefficient μ_r is function of materials in contact and their roughness [04], [05]. For example, for pneumatic tires on loose sand, $\mu_r = 0.2 - 0.4$, while for same tires on asphalt, $\mu_r = 0.02$. The pressure in the tires is also influencing the rolling resistance coefficient.

The drag force F_d can be defined as:

$$F_d = \frac{1}{2}\rho c_d A v^2 \tag{04}$$

The significance of the parameters involved in equation (04) is:

- ρ - Density of air at normal temperature and pressure conditions, expressed in kg/m^3
- A - Characteristic frontal area of robot, expressed in m^2
- v - Linear velocity, expressed in m/s
- c_d - Drag parameter

The drag parameter c_d is function of several other parameters used in aerodynamics, including Reynolds, Froude and Mach Numbers. The roughness of the characteristic area of the robot is also influencing the drag parameter. For modern cars, $c_d = 0.30$ and for non-optimized old cars like T Model of the Ford's of the 1920's, $c_d = 0.70 - 0.90$.

The power requirements for the rechargeable batteries of the robot discussed in this paper are roughly 500W. The estimation considers the torque requirement for the two DC motors involved on traction, all other servo systems, sensors and electronics. The service time is extended by recharging the batteries with two solar panels with photovoltaic cells.

Vibration Analysis

The wheels of autonomous robot experiences mechanical vibrations while moving on rough terrain. Let $y_w(t)$ denote the displacement of the wheels on vertical direction and $y_G(t)$ the displacement of the center of mass of the robot from its static equilibrium position at arbitrary time t. The net elongation of the springs in the suspension is $y_G(t) - y_w(t)$, the relative velocity between the ends of the dampers is $\frac{dy_G(t)}{dt} - \frac{dy_w(t)}{dt}$ and the differential equation of motion of the system involves the stiffness of the springs k and the damping coefficients c:

$$m\frac{d^2y_G}{dt^2}+c\left(\frac{dy_G}{dt}-\frac{dy_w}{dt}\right)+k\left(y_G-y_w\right)=0 \tag{05}$$

If the undulations of the ground are approximated as $y_w(t)=Y_w\sin\omega t$, then the differential equation of motion (05) becomes:

$$m\frac{d^2y_G}{dt^2}+c\frac{dy_G}{dt}+ky_G=kY_w\sin\omega t+c\omega Y_w\cos\omega t=A\sin\left(\omega t-\alpha\right) \tag{06}$$

The significance of parameters A and α is:

- $A=Y_w\sqrt{k^2+\left(c\omega\right)^2}$
- $\alpha=\arctan\left(-\frac{c\omega}{k}\right)$

Equation of motion (06) shows that the excitation of the wheels due to the movement on rough terrain is equivalent to the application of a harmonic force to the center of mass of the robot [06], [07], [08]. The steady-state response of the center of mass can be expressed as:

$$y_{pG}\left(t\right)\frac{Y_G\sqrt{k^2+\left(c\omega\right)^2}}{\sqrt{\left(k-m\omega^2\right)^2+\left(c\omega\right)^2}}\sin\left(\omega t-\phi-\alpha\right)$$

$$\phi=\arctan\left(\frac{c\omega}{k-m\omega^2}\right) \tag{07}$$

Using trigonometric identities and introducing the damping coefficient ς equations (07) can be written in more convenient forms:

$$y_{pG}\left(t\right)=\frac{Y_G}{Y_w}\sin\left(\omega t-\phi\right)$$

$$\frac{Y_G}{Y_w}=\sqrt{\frac{k^2+\left(c\omega\right)^2}{\left(k-m\omega^2\right)^2+\left(c\omega\right)^2}}=\sqrt{\frac{1+\left(2\zeta r\right)^2}{\left(1-r^2\right)^2+\left(2\zeta r\right)^2}} \tag{08}$$

$$\phi=\arctan\frac{mc\omega^3}{k\left(k-m\omega^2\right)+\left(\omega c\right)^2}=\arctan\frac{2\zeta r^3}{1+\left(4\zeta^2-1\right)r^2}$$

The ratio $T_d=\frac{Y_G}{Y_w}$ of the amplitude of the response $y_G\left(t\right)$ to that of the wheel motion $y_w\left(t\right)$ is termed displacement transmissibility. The variations of T_d and ϕ given by the equations (08) are generated in Matlab and shown below for different values of frequency ratios $r=\omega/\omega_n$ and damping ratios $\zeta=c/2m\omega_n$.

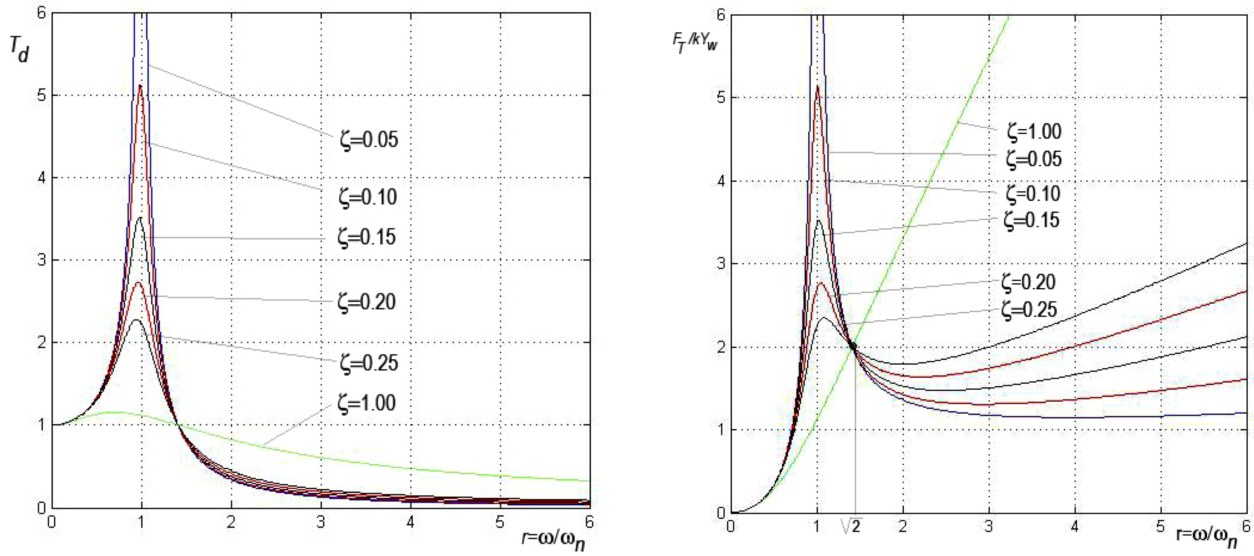


Figure 6. Variation of T_d and Transmitted Force F_T/kY_w with Frequency Ratio for Different Damping Ratios ζ

It is important to notice the following aspects related to the families of plots from Figure 6:

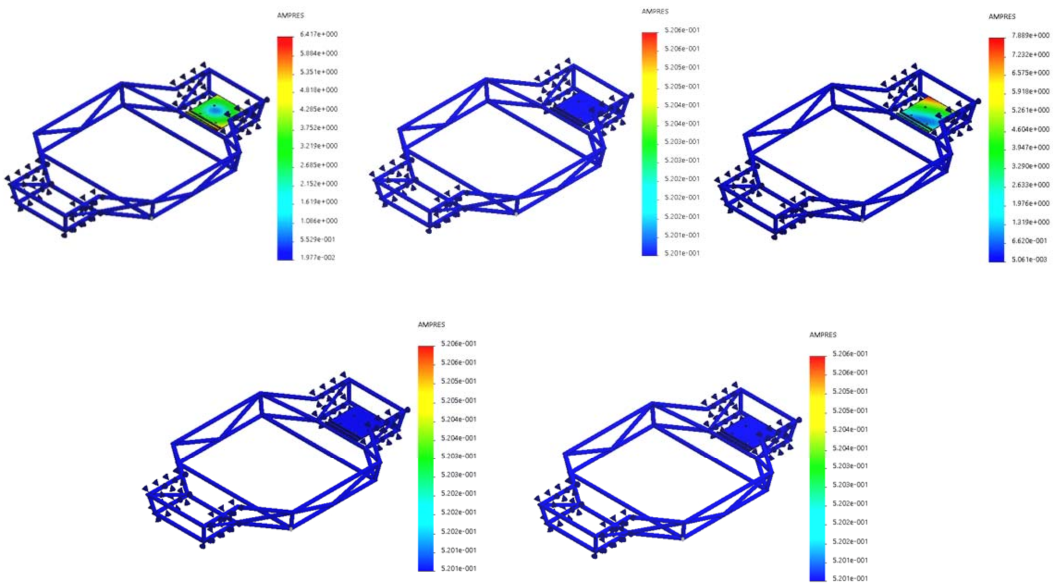
- The displacement transmissibility is $T_d = 1$ at $r = 0$ and close to unity for small values of r
- For damping ratios $\zeta = 0$, $T_d \to \infty$ at $r = 1$ - resonance
- The displacement transmissibility is less than unity for $r > \sqrt{2}$ at any amount of damping ratios $\zeta \neq 0$
- The displacement transmissibility is $T_d = 1$ for all values of damping ratios ζ at $r = \sqrt{2}$
- For $r < \sqrt{2}$ smaller damping ratios lead to larger values of T_d. On the other hand, for $r > \sqrt{2}$, smaller values of damping ratio lead to smaller values of T_d
- The displacement transmissibility T_d attains a maximum for $0 < \zeta < 1$ at the frequency ratio $r_m < 1$ given by:

$$r_m = \frac{1}{2\zeta}\sqrt{\sqrt{1+8\zeta^2} - 1}$$

- The displacement transmissibility is minimized for large values of frequency ratios, but at such $r = \omega/\omega_n$ ratios the force transmitted to the robot can be minimized only for small damping ratios

In autonomous robots minimal displacement transmissibility is a requirement due to the need for live imaging, achieved only with steady cameras – see illustration from Figure 4. Such minimal displacements require a robot with optimized stiffness, due to the fact that the fundamental natural frequency is function of both the mass of the robot and its stiffness, $\omega_n = \sqrt{k_r/m_r}$. The main contributor to both mass and stiffness of the robot is the chassis.

Due to the complex 3D geometry of the chassis, the authors considered numerical approaches for modal analysis. The simulations were performed in CosmosM with a 3D CAD model of the chassis designed in SolidWorks – see illustrations from Figure 7. The modal and harmonic analysis – not discussed in this paper - are used in the process of optimizing the design of the robot.



List Modes

Study name: Modal Analysis

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	›eriod(Seconds
1	0.42252	0.067246	14.871
2	0.53373	0.084946	11.772
3	0.62563	0.099572	10.043
4	0.8087	0.12871	7.7695
5	0.8096	0.12885	7.7609

Close Save Help

Mass Participation (Normalized)

Study name: Modal Analysis

Mode No.	Freq (Hertz)	X direction	Y direction	Z direction
1	0.067246	6.6515e-031	3.7344e-031	1.4599e-032
2	0.084946	1	0	0
3	0.099572	1.0996e-033	6.1907e-030	2.8594e-032
4	0.12871	0	1	0
5	0.12885	0	0	1
		Sum X = 1	Sum Y = 1	Sum Z = 1

Close Save Help

Figure 7. Results of Modal Analysis for the Chassis of the Robot

Conclusions

The development and design of unmanned ground vehicles is a complex task involving integration of electronics and mechanics, optimization related to terrain conditions, performance and reliability in operation. The authors considered such parameters in mechatronics integration, evaluation of the power requirements and mechanical optimization of the robot by vibration analysis and Finite Element Modeling, with important benefits in minimizing sensor errors.

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Biographies

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