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DESIGN OF A STAIR CLIMBING TWO WHEELD ROBOT

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Abstract: *This paper presents the innovative design of a mobile robot capable of navigating through varied terrain and climbing up obstacles. For the surface motion a system of two independently actuated wheels was used in order to confer a high flexibility and manoeuvrability to the robot. For the climbing part a screw-nut mechanism was used to lift up the robot and at the same time change its centre of gravity as to provoke a fall at a selected high.*
Key words: *mobile robot, stair climbing*

1. INTRODUCTION

If the industrial robotics field is relatively well statured, the area of service robots is in full development. This paper presents the design of a mobile wheeled robot intended for inspection and surveillance operations.
To satisfy the operational requirements the robot must be as small as possible, as flexible as possible. It also must be easy to maintain, easy to control. There are such structures on the market but they rarely satisfy the requirements to the full extent, and when they do, it is quite costly.
The military has attempted to insert robotic technology into aerial platforms since World War I, where attempts primarily focused on remotely controlling dirigibles. The first real breakthrough was in World War II when a modified B-17 successfully performed unmanned flights. Unmanned Aerial Vehicles (UAVs) have had much more success than their ground counterparts because they do not have to contend with obstacles and the means by which aerial vehicles maneuver is easier to control.
The lack of obstacles (for the most part) and similar flight characteristics as aircraft have also allowed Unmanned Underwater Vehicles (UUVs) to progress faster than robotic ground vehicles. Additionally, UUVs became essential for exploration, rescue, and recovery operations in the vast ocean depths.
On the other hand, requirements for robotic ground vehicles were often seen as a luxury or unjustifiable. In addition to UUVs with submarine or aircraft like features for water operations, there is also an almost science fiction looking crab called the Autonomous Legged Underwater Vehicle (ALUV) as shown in Figure 1.

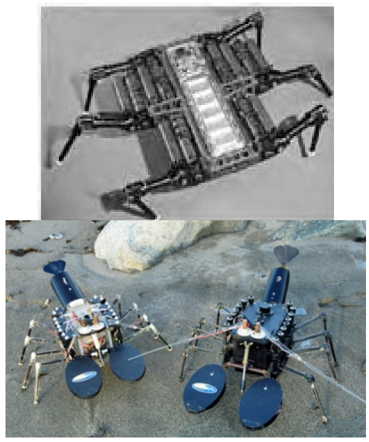


Figure 1. ALUV [10]

John Blitch of the Defense Advanced Research Projects Association (DARPA) has established five imperatives that a mobile robotic structure must meet in order to be considered able and capable to ensure mission success. These imperatives will help by addressing the key environmental and operational requirements such as:

- Overcoming potential obstacles,
- Communicating significant distances,
- Operating in hostile areas,
- Anti-handling protection (prevent unwanted handling or tampering),
- Functioning autonomously (maneuver without commands from an operator), or not needing humans to rescue them when something goes wrong.

Under certain mission scenarios, one or more of the imperatives could be relaxed; but as a general rule, a mobile robotic structure should be able to meet them all.

Numerous robotic systems and sensors are available. Many were developed for commercial uses and are ideal for commercial off-the-self (COTS) acquisitions. Universities and private industry have also developed various systems ranging from anatomically functioning legs to systems that operates on Mars.

Lemming. The Foster-Miller Inc. TMR Lemming family began as amphibious robotic platforms as shown in figure 2. They have evolved into numerous other platforms to include the Lightweight Unexploded Ordnance Reconnaissance (LUXOR) and its unexploded ordnance-handling partner Tactically Adaptable Lemming Ordnance Negotiator (TALON). They can be controlled either by preprograms or operator commands via a wire or fiber optic tether, radio frequency (RF) signals or ultra wide (UW) acoustic modems.

Figure 2. Foster-Miller Lemming [11]

2. THE CONCEPT

The statement was to create a mobile structure with a small form factor, capable to navigate through varied terrain (climb up building stairs, roll on flat or inclined surfaces), at high speed. As a possible application we thought for the surveillance of a building with more than one level. This would imply that the robot would have to be able to climb over stairs, turn around corners, go down the stairs.

Starting from these premises a list of requirements was established. Some of the identified requirements were:

- Should be highly flexible to be able to turn around corners and climb over obstacles,
- To be able to cover a large surface it should have a high autonomy,
- Since it is supposed to work more or less autonomously, an increased dependability is desirable,
- High resistance to shocks caused by dropping or falling,
- High movement speed,
- …

Once established the specific requirements that the structure must satisfy, an AHP (Analytical Hierarchy Process) analysis was done in order to determine which of them are the most important. The first five – accounting for more than 80% importance out of the total (figure 3) – most important requirements identified were:

1. High maneuverability 21.39%
2. Simple structure 19.81%
3. Rough terrain navigation 15.92%
4. Easy to control 14.84%
5. High dependability 12.14%

High maneuverability means to present an as high as possible and as necessary degrees of mobility. Through a simple structure we understand the use of a minimum number of parts needed to fulfill a given task. Rough terrain navigation means to be able to go on flat or inclined surfaces as well as go over obstacles.

AHP	high authonomy	high manouvrability	easy to controll	simple structure	low volume	capable to navigate through rough terrain	high dependability	high movement speed	Importance %
high authonomy	1.00	0.33	0.33	1.00	1.00	1.00	1.00	3.00	7.73
high manouvrability		1.00	9.00	0.33	9.00	0.33	1.00	3.00	21.39
easy to controll			1.00	3.00	3.00	1.00	1.00	3.00	14.84
simple structure				1.00	3.00	9.00	1.00	3.00	19.81
low volume					1.00	1.00	0.33	0.33	4.2
capable to navigate through rough terrain						1.00	3.00	9.00	15.92
high dependability							1.00	9.00	12.14
high movement speed								1.00	3.97

Figure 3. Analysis of requirements using AHP (Spread sheet template)

Using the VOCT II (Voice of the customer table part II) method the requirements were translated into product characteristics. Some of these characteristics are conflicting in several aspects. The robot is required to have a simple structure but at the same time accommodate a large number of parts to satisfy the high maneuverability requirement. It must have a large number of motors to allow for a high maneuverability but at the same time have as few as possible in order to ensure a high dependability and autonomy.

Through using innovative problem solving method TRIZ 40 (the 40 inventive principles of TRIZ – Russian acronym for "Theory of inventor's problem solving") a compromise was attained.

TRIZ is a theory that considers engineering problems and suggested solutions based on their structure. TRIZ states that: technical systems evolve towards the increase of ideality by overcoming contradictions, mostly with minimal introduction of resources, and most of the innovations are transpositions of known solutions in other fields. [6]

One identified conflict: Simple structure ≠ High maneuverability. Simple structure can be interpreted as element 36 – Device complexity which has to be as low as possible. High maneuverability means 35 – Adaptability or versatility and it has to be as great as possible. Using TRIZ 40P, four Principles were identified as possible solutions to the conflict: 15. Dynamics, 28 Mechanics substitution, 29. Pneumatics and hydraulics, 37. Thermal expansion.

To solve the first conflict, the principle 13 – Dynamics was considered. One direction proposed by this principle states: "Divide an object into parts capable of movement relative to each other." This lead to the conceptualization of a 2 wheeled structure that was able to move on planar surfaces, having the wheels actuated by motors situated in a box in between the wheels. The box has the center of gravity below the wheels axis (see figure below).

A second conflict: Rough terrain navigation (which implies a relatively complex device) ≠ Easy to control (with respect to reliability that requires a low number of parts). The TRIZ Matrix proposes the following Principles to solve this contradiction: Improving 36 – Device complexity, without damaging 27 – Reliability: 1. Segmentation, 13. The other way round, 35. Parameter changes.

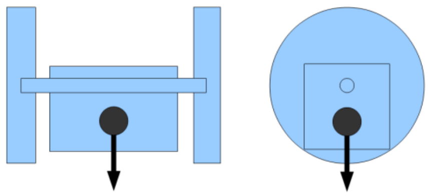


Figure 4. Front and side view of the concept

For the second conflict the Segmentation principle was considered through separating the planar movement mechanism from the obstacle surpassing mechanism.

The final concept is composed out of:

- two wheels on each side – allowing for linear and yawn movement,
- a trapezoidal body in between the wheel – having the center of gravity below the wheels common axes
- a slightly tilted screw-nut mechanism that allows the structure to rise itself and when reaching a given height to fall. For a better understanding of the function of the screw-nut mechanism see figure 5.

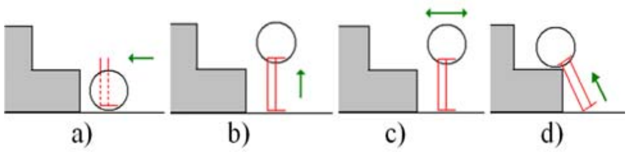
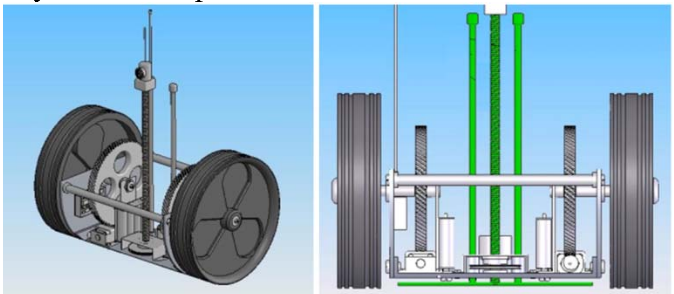


Figure 5. Working of the screw-nut mechanism

As seen in the figure above the working of the screw-nut mechanism is as follows: a) the robot encounters an obstacle and it stops, b) the mechanism engages, pushing the screw onto the floor and raising the body of the robot over the obstacle, c) because of the tilt of the mechanism the robot falls over the obstacle, d) the screw is retracted and the process can start all over again.

3. MATERIALISATION OF THE CONCEPT

At first the concept was developed using CAD software. SolidWorks 2008 software package was used to create the rough assembly and the key individual parts.



a) b)

Figure 6. a) Isometric view of the "virtual" robot structure,
b) Frontal view of the robot – lifting mechanism emphasized

Having done the assembly, the mechanisms were designed. The two wheels are actuated using electric DC motors and a warm gear transmission. The screw-nut mechanism is also actuated by an electric DC motor through a rubber belt transmission.

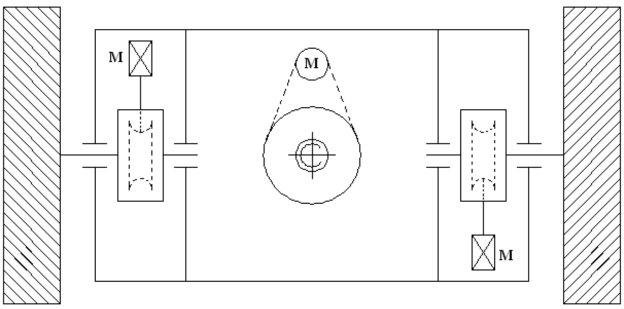
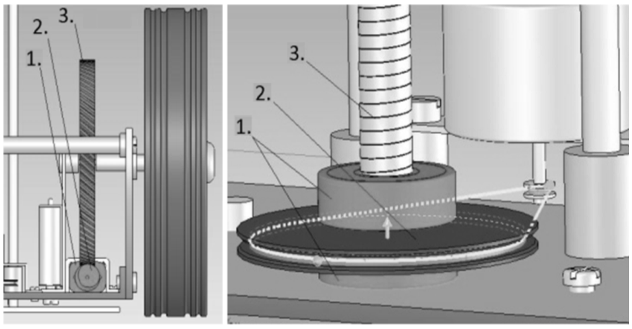


Figure 7. Diagram of the robot

The next step was the mechanical calculation of the mechanisms.
The motion on a planar surface is ensured by the two wheels that are actuated through a warm gear mechanism by a DC electric motor *NF243G-10.*



a) b)

Figure 8. a) The wheel mechanism: 1 – motor, 2-3 – warm gear speed reducer; b) Screw-nut mechanism: 1 – ball bearings, 2 – belt wheel & nut, 3 – screw.

4. DETERMINING THE POWER REQUIREMENTS

Having finished the 3D model of the robot with the appropriate material for each part, by using the Mass properties command of Solid Works the total mass of the robot was determined to be: G = 4,506 kg.
It was imposed that the robot be able to travel at a maximum velocity of 20 m/min.
Considering the inertia force:

$F_i = G\left(A + 9.81\,\frac{m}{s^2}\right)$ and a transmission ratio for the warm gear speed reducer of I = 20 the motor torque was determined to be: T_m= 7.274 W.
A Johnson Electric DC motor NF243G-102 was chosen to power the wheel, having a motor torque of 8.70 W.

5. WARM GEAR SPEED REDUCER DESIGN

Next, the warm gear speed reducer and the screw-nut mechanism were designed.
Mechanical transmissions are characterized by the transmission ratio and the efficiency:

$$I = \frac{n_1}{n_2}\ ;\ \eta = \frac{P_2}{P_1}\ , \qquad (1)$$

where:

- I – transmission ratio,
- n_1 – input rotational speed,
- n_2 – output rotational speed,
- η – efficiency,
- P_1 – input power,
- P_2 – output power.

For worm gears the number of teeth z_1 is considered to be 1…4 regarding the transmission ratio [ADA94].

Considering the radius of the worm wheel r_0 and the helix pitch p_x for one rotation of the worm wheel the step can be computed using the formula:

$P_E = z_1 \cdot p_x$ (2)

The geometrical elements of a worm gear are presented in the figure 10.

Where:

- θ_0=twist angle of the helical tooth ;
- β_0=twist angle of the helical tooth with respect to the cylinders axes.

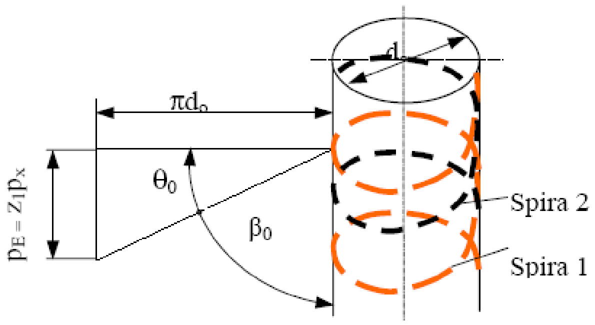


Figure 9. Theoretical representation of a worm-wheel helix

For a complete determination of the geometry of the worm gears the following standards were considered: STAS 822-82, STAS 915/1-81, STAS 915/2-81, STAS 915/5-81, STAS 6461-81, STAS 6845-82, STAS 12192-84.

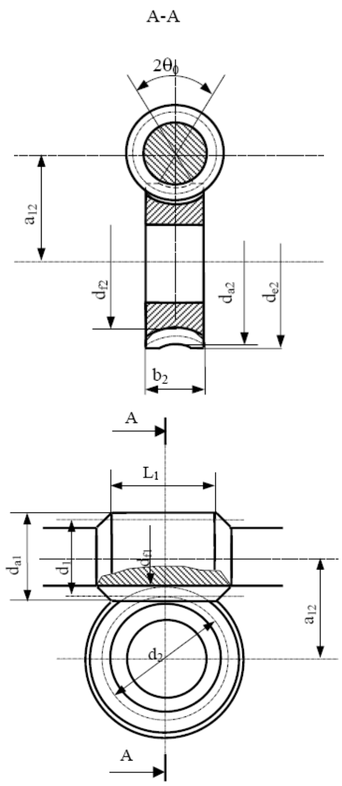


Figure 10. Worm gear (geometrical elements)

6. SCREW-NUT MECHANISM DESIGN

The purpose of the lifting mechanism is to allow the mobile platform to be lifted in the air at a given height. This height might vary if the terrain is not entirely flat. Also, low power consumption was desired in order to increase the autonomy of the robot as much as possible. For these considerations a screw-nut mechanism was chosen. It allows for a very effective power transmission with regard to the lifting operation and also in case of power failure during the operation it will automatically lock the platform at the reached height, reducing the risks of damage by uncontrolled fall.

Considering the static force acting on the screw to be F = 44.15 N and the maximum height to be reached of h = 215 mm at a negligible speed, the mean diameter of the thread was determined using formula 3.

$$D_2 = \sqrt{\frac{F}{\pi \cdot \psi_h \cdot \psi_m \cdot q_a}} \text{ [mm]} \quad (3)$$

Where: Dimensional factor: $\psi_h = 0.5$, Length factor of the nut thread: $\psi_m = 1.2 \ldots 2.5$, $\psi_m = 2$, admissible squashing strength: $q_a = 6 \ldots 7$, $q_a = 6.5$ [N/m].

A value of 1.47 mm was determines, so by choosing an M8 ISO thread the conditions should be satisfied.

7. MOCKUP OF THE ROBOT

Having in mind the specific requirements and the engineering constraints a fully functional mockup of the robot was created. Considering most of the elements used in the virtual prototype and the constraints imposed by the mechanical computations, the appropriate motors and gears were selected, and with slight modifications were assembled into the structure that can be seen in figure 11.

Figure 11. Concept and model of the robot

8. CONCLUSION

Pending the study in the field of mobile robots and design of the proposed structure using competitive engineering tools, a new mechanical architecture was devised to surpass the constraints encountered.

Using TRIZ an innovative solution was attained. In the end the resulting structure is able to overcome varied obstacles, climb stairs, and navigate on flat surfaces with high flexibility and speed.

Based on the 3d designed model a mockup was realized to better study the dynamics of the robot. With minor adjustments to the initial design, the structure performed well in all the trials.

Further development can include increased autonomy (present 1.3 hours), several sensors in key areas and artificial intelligence,

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PROIECTAREA UNUI MINI ROBOT CU DOUA ROŢI CAPABIL SĂ URCE SCĂRI

Rezumat: Lucrarea prezintă dezvoltarea inovativă a unei structuri capabile să navigheze pe teren variat şi să depăşească obstacole. Pentru miscarea in plan se utilizează un sistem de două roţi acţionate independent, pentru o flexibilitate şi o manevrabilitate crescută în navigare. Pentru partea de depăşire a obstacolelor un mecanism surub-piulită este folosit pentru a ridica structura. Mişcarea de ridicare provoacă şi o deplasare a centrului de greutate a structurii ceea ce provoacă o răsturnare a acesteia la o înălţime stabilită.

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