Developing a new mobile robotic structure for search and rescue operations

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Abstract. In this paper will be discussed the subject of robot intervention in situations where man cannot safely intervene. So, the main goal of this research is the development of a mobile robotic structure with off-road capabilities that can move around disaster areas. To achieve this goal, a mechanical structure able to overcome any obstacles, has been designed, simulated and optimized. The locomotion problems of the proposed robot were solved with complex kinematics, based on adapting the structure to the work environment. The robot is provided with a rolling drive system around the body. When encountering with an obstacle, the structure will roll, with the aid of the tail fixed on the robot body.

1. Introduction

Search and rescue (SAR) operations involve a high risk to human lives, both to the victims and to those sent in to save them. So, an appropriate solution would be the use of robots in this type of operations, involving lower costs and improved efficiency. The development of mobile robotic structures is a topical subject, being reflected also by the development of a special domain of robotics / mechatronics - Mobile Robotics. Of all these systems, the robots equipped with tele-operability capabilities, usable as systems able of carrying out investigation, monitoring tasks, etc. are significant, in situations where people can not intervene. The idea of search and rescue robots appeared in the early 1980s [1]. However, until 1990 there was no real development in this area. Although, robots are not widely used in real search and rescue operations while the evolution in this area seems quite promising.

At first glance it may seem quite simple - we need robots that could penetrate through the rubble and find people underneath. There are several things that might go wrong and affect a certain part of the population. There may be fires, tsunamis, earthquakes and man-made disasters such as Chernobyl or 9/11. Some of these disasters can create similar consequences; some, on the other hand, may be quite unique. Two of the most common situations are urban search and rescue (USAR) [2] and search and rescue in an extended area. These situations can be caused both by people and by their nature. If we are dealing with a search and rescue situation in an urban environment, rescuers usually must deal with collapsed buildings, victims trapped underneath, and other unique problems for such an environment.

Analyzing, in the current context, the use of these types of mobile robots, represents a solution to many problems, which will be listed as follows:
- Recognition and mapping (a particularly important task in natural disasters);
- Search for victims of accidents (victims must first be found in order to save them);
- Structural inspection of buildings, provision of data for a preliminary medical assessment;
- Telepresence (the rescue robot - the "eyes and ears" of a team member who is outside the dangerous area);
- Detection of gas leaks, hazardous substances, etc.

After long documenting, several robotic structures have been identified as providing optimum support to the search and rescue recipients. An example is the NIFTi [3] robot, presented in the figure below, who was funded by the European Union, as a remote-operated robot that has been following the 2016 disasters in Italy. Scorpion and Kohga3 are also presented, describing structures developed by Japanese research teams that intervened in the Fukushima disasters [4]. Two builds from the Military Environment, Scout and Talon, were used to rescue the World Trade Center. The last variant, developed by a team at the University of Pittsburgh, is based on the movement of a snake, and possesses the advantage of effortless mobility through narrow spaces.

![Figure 1. Search and rescue robots: a) NIFTi [3]; b) Toshiba Scorpion [4]; c) Talon [5]; d) Kohga3 [6]; e) Scout Recon [7]; f) Snake [8]](image)

Concluding, the structures described above are structures of military research or namely research projects, most of which representing tracked robots with large dimensions and very high costs, some with arms and prehensile extensions. Apart from Scorpio and Snake, who communicate via cable, the other structures are radio controlled.
2. The robot designs

The proposed structure (shown in figure 2) - one with four motor wheels (4) positioned two by two on a lever (2), articulated in the middle of the robot body (1). At the encounter of an obstacle, the structure will roll, supported by the tail (3) that is rigidly fixed on the robot shell.

![Figure 2. The robot concept.](image)

Starting from the concept presented below (figure 2), the design of the mechanical structure was launched. The robot is composed of three assemblies: 1 – body assembly; 2 – turning assembly and drive wheel assembly, as they are listed in the figure 3.

![Figure 3. Body subassembly.](image)

The robot body subassembly, presented in figure 3, is formed by a rigid body made from bended aluminum sheet (1) and two caps (2) assembled by M3 countersunk screws. The rigid tail (3) is fixed on one of the cap. To provide a rotary coupling between the body and turning assembly, two pillow block flanged ball bearings KFL08 (8) were fixed on the rigid body (1). As an actuator for the revolution mechanism, a servomotor (4) will be used, in accordance with the dimensioning presented in the following section. The servomotor is fixed by two rigid blocks (7) on the body. In order to transmit and amplify the movement produced by this actuator, a spur gear transmission was used. To ensure the drive spur gear (5) to the actuator spindle, an adapter (6) was made from a servomotor horn.
In figure 4 is illustrated the turning subassembly. This is constituted by a central shaft (2) and two parallel and synchronized levers (1) fixed to the shaft. To ensure a constant radius and symmetry of the turning mechanism, the levers were fixed on the shaft at halfway between extremities.

![Figure 4. Turning subassembly.](image)

For limiting the axial movement of the shaft, and implicitly, the movement of the mechanism, relative to the body, two retaining rings (8) have been used. The other half of the transmission mechanism, namely the driven spur gear (5) is joined to the shaft by the hub (6) and socket set screws (7).

![Figure 5. Lever-shaft joint.](image)

A good functioning of this mechanism is obtained only if the levers are synchronously rotated. A solution is presented in the figure above; the ends of the shaft (2) are threaded and milled to obtain a keyway, as shown in the figure 5. A similar keyway was executed on the levers, which were subsequently joined by the washer (4) and nut (3).

For completing the turning mechanism, four DC geared motors (9) have been used to drive the wheels. The motors are protected by the enclosures (10).
The complete structure of the designed robot is portrayed in figure. It can be observed that the body, the turning mechanism, and also the driving wheels have been mounted by hexagonal hubs to the DC motors of the turning mechanism.

![Figure 6. The design robot structure.](image)

3. Mechanism and servomotor dimensioning

The most intensive task that the robot must do is the rolling operation in order to overcome an obstacle. Two situations are studied: one in which the DC geared motors of the wheels perform the turning and the second one in which the turning is generated by the central servomotor.

The structural analysis of the robot mechanism consists in determination of the kinematic joints, establishing the mobile links, determination of the degree of freedom of the mechanism, drawing up the structural scheme, establishing the structural groups, drawing up the multipolar scheme and writing the structural relation. Based on the structural analysis, the kinematic and kinetostatic analysis of the mechanism are performed.

![Figure 7. A representation of the: a) CAD model; b) equivalent kinematic scheme.](image)

For these computations is considered that the robot is stopped in front of an obstacle that cannot be overcome without performing the rolling and there is no slippage. In the figure 7 the turning assembly is link (1), the body assembly is link (2) and the contact of the tail with the ground is link (3). The center of the front wheels is considered to be the revolute joint (A) that is positioned right on the Oy axis. The radius of the wheel is taken under consideration; segment (OA). The revolute joint (B) connects link (1) and (2). The tail contact with the ground is broken down to two inferior joints: revolute joint (C), and prismatic joint (D), the segment (CD) being a zero-length element. As described, the studied mechanism resembles with a slider-crank mechanism with an eccentric element.
In case that the DC geared motors generate the overturning of the platform, the active revolute joint is in (A). For the mechanism analysis, if there are considered the relative motions between the links, it is noticed that the mechanism has the following inferior joints (three revolute and one prismatic: A(0R1), B(1R2), C(2R3) and D(3T0). The mobile links of the mechanism are 1(A,B), 2(B,C) and 3(C,D). Considering the number of the mobile links and the number of the kinematic joints, results the degree-of-freedom of the mechanism, namely: \( M = 1 \).

The structural analysis continues in figure by presenting the structural scheme (a) of the robot mechanism. From the structural scheme is observed that the mechanism is composed of base \( Z(0) \), the motor group \( R(1) \) and the dyad of aspect 1, \( RRT(2,3) \), (joint D being a prismatic joint). With the help of these modules, has been drawn up the multipolar scheme (figure b).

![Figure 8. Structural analysis for the first case: a) Structural scheme, b) multipolar scheme](image)

For the initial kinematic computation, the following starting values are used: link \( AB = 0.190 \) m, \( BC = 0.615 \) m, \( CD = 0.000 \) m and \( OA = 0.057 \) m. The mass of the link 1 is 1.260 kg and the second link has 1.140 kg. The moments of inertia for both links are determined and taken under consideration.

The kinematic analysis of the mechanism consists in the determination of the positions of links 2 and 3, the angular velocity and acceleration of link 2, as well as the relative velocity and acceleration in the prismatic joint D. Once established these parameters, it can be determined the positions, the velocities and the accelerations of any point on the mechanism’s links.

The initial position in which the robot starts the overturning operation mechanism is considered to be the situation in which the links (1) and (2) are in extension and the joint (B) is in its starting position \( B_0 \). The slider’s stroke is the distance measured on the sliding path between the two extreme positions (figure). Analytical, this distance is determined with the relation:

\[
C_{\text{stroke}} = \left( (AB + BC)^2 - AO^2 \right)^{1/2} + \left( (BC - AB)^2 - AO^2 \right)^{1/2}
\]  

(1)

The \( \phi_1 \) angle is measured between the Ox axis unit vector and the link AB in trigonometric way, its initial value is determined with the relation:

\[
\phi_1 = \arcsin \frac{AO}{AB + BC} = -0.0741417374[\text{rad}]
\]  

(2)

Determination of the kinematic parameters of point B has been done with the help of the A1R procedure, corresponding to the motor group R(1) and for the dyad’s links RRT(2,3) has been made with the D2PVA procedure, the procedures being described in [9].

Few of the determined parameters are plotted in figure. These parameters are the most significant for the robot’s variable structure: dependence of \( \phi_1 \) and point C stroke with respect to \( \phi_1 \). In real life cases, the angle \( \phi_1 \) has values between 0… 3/4\( \pi \) radians, but in kinematic analysis has been taken under consideration the general situation in which the variation is from -0.074…2\( \pi \) radians.
Figure 9. The slider’s stroke.

Figure 10. Kinematic parameters variation charts:
   a) dependence of $\phi_2$ on $\phi_1$, b) dependence of point C stroke on $\phi_1$.

If the central servomotor generates the overturning of the platform, the active revolute joint is in this case the joint (B). Now for the mechanism analysis must be considered complex motor group (RRaRT). The mobile links of the mechanism are still the previous ones: 1(A,B), 2(B,C) and 3(C,D). The structural analysis in this particular case: the mechanism has a base Z(0), and one motor group (RRaRT), the structural and multipolar scheme being shown in figure.

Figure 11. Structural analysis for the second case:
   a) Structural scheme, b) multipolar scheme.
The kinematic parameters in this second case in which the active joint is (B), varies roughly the same as in the previous case. Significant differences appear when the kinetostatic analysis is performed as described in [9] for the both cases. The most important parameter determined in this analysis is the required torque needed to overturn the robotic structure.

In figure 12 is presented, in the first case, the diagram of the required torque if the motor is mounted in joint (A) with respect to $\phi_1$. Maximum torque obtained is 4.77 Nm. In the second case presented in the same figure, the motor is considered to be mounted in the joint (B), with a maximum required torque 3.64 Nm, also referenced to $\phi_1$ for a better comparison. For both cases, the angle $\phi_1$ variation is only from -0.074…1.5 radians.

In the first case, even if the required torque is split between two DC geared motors (in real case two wheels will be in contact with the obstacle and the ground), a value of 4.77 Nm is too high for this robot overall characteristics. Because the robot has a symmetrical structure, in an overturning situation only a pair of the DC geared motor will be actuated, the other pair acting as additional payload that must be moved. Moreover, wheel slippage can occur, and thus the power consumption will be greater than the one anticipated, limiting the robot’s energy autonomy. For the reason, the first case is avoided as main overturning generator.

The central servomotor situated at the intersection of the link (1) and (2), in the first case was shut down and the joint (B) was a passive one. In the second case, the central servomotor generates the overturning of the robot, and the four DC geared motors are shutdown. The maximum torque of 3.64 Nm in this situation is generated by just one motor that does not have a counterpart, thus reducing the additional payload. This case is preferable also since the structure will overturn based on an internal deformation ensuring the desired result. Also, this variant is preferable due to a simpler electronics module and a small acquisition costs compared to the previous considered case.

4. Controlling the robot

To control the robot, an Arduino Nano board based on the ATmega328 microcontroller, two dual full-bridge drive L298 was used (figure ). A problem was encountered when connecting the motors to the L298 driver. Due to the fact that the mechanism has a continuous rolling motion (we cannot bring the mechanism to the initial position after each rotation as it would return the robot to the previous position), direct connection with wires is not possible. The solution used was a hollow slip ring Orbex 512-0600, 6 wires, 2 A (presented as (11) in figure).
As a power supply for the DC motors and central servomotor, a Li-Po 3 cells 2000mAh battery pack has been used. To provide a 5 V logic TTL level for L298 drivers and HC 05 Bluetooth adapter, and also to power the Arduino Nano board, a L7805 voltage regulator is adopted. Arduino board wasn’t powered through the V_{in} pin because the voltage of the battery is higher than 12V, the maximum allowed voltage for V_{in}. The chosen solution was to bypass the internal regulator and use an external one, to power Arduino through the 5 V pin.

The robot control is conducted by Bluetooth communication with an Android Smartphone. For this, a serial Bluetooth adapter HC05 was used. As an actuator for the rolling mechanism a FT6560M metal gear high torque servo is chosen.

5. Program description
The logic of the main program is presented in the figure. The program starts by checking the availability of the serial connection between arduino and smartphone. If there is no connection, it will send a massage through the serial terminal, naming ‘No serial connection’. If the connection is successful, the interface will be awaiting a character. In the situation of sending ‘F’ it will go to the Forward subroutine. For the rest of the moves, characters have been defined as follows: ‘B’ for Backwards, ‘R’ for Right, ‘L’ for Left, ‘S’ for Stop and ‘T’ for rolling/turning. These subroutines are similar, with the exception of the revolving direction. As an example, the forward subroutine will be described below:

```c
void Forward ()
{
    analogWrite(enm1, 255); //setting the motor speed 0…255 for motor1
    digitalWrite(m11, HIGH); //direction for motor1
    digitalWrite(m12, LOW);
    analogWrite(enm2, 255); //setting the motor speed 0…255 for motor2
    digitalWrite(m21, HIGH); //direction for motor2
    digitalWrite(m22, LOW);
    analogWrite(enm1, 255); //setting the motor speed 0…255 for motor3
}```
digitalWrite(m11, HIGH);  //direction for motor3
digitalWrite(m12, LOW);
analogWrite(enm2, 255);  //setting the motor speed 0…255 for motor4
digitalWrite(m21, HIGH);  //direction for motor4
digitalWrite(m22, LOW);
Rservo.write(90);  //servo speed 0
}

Figure 14. Logic diagram of the main program.

The differences between the subroutines are motor speeds and directions, and in turning, the servo speed value is 180 while all others are 0.

6. Android Application
The application used for controlling the robot is ‘Bluetooth controller’ (figure 15) available in android market. This app allows key definition and has a terminal window for the robot communication. For setting the keys, in the right upper corner, a button is available. For each button is required to specify the label and the character to be sent through the Bluetooth connection. This commands and characters are described in the section above. To connect the smartphone to the HC005 Bluetooth adapter, a prior pairing from android is needed. The pin code for connecting to the adapter is ‘1234’. The application admits up to nine buttons to be created, but in our case six are used.

By pressing one of the buttons, the robot moves only one step. For obtaining a continuous movement, the button mustn’t be released. For rolling/turning operations, the corresponding button needs to be pressed only once. The subroutines enact until the mechanism makes one turn and afterwards return to the starting position (the axis of the lever is parallel to the axis of the tail, which is also the body axis).
7. Experimental scenario and Conclusions
The primary purpose of this research was to develop a robot structure capable of successfully overcoming any obstacle that would appear on its trajectory. A solution was designed, a four-wheel robot with a rolling mechanism described above, with the main advantage: it can overcome far bigger obstacles than the ground clearance of a classic robot with wheels.

To prove this, an experimental scenario is illustrated in figure. One of the greatest obstacles this robot can encounter in search and rescue operations are stairs in a collapsed building after an earthquake or other natural disasters. So, our scenario involves a staircase. Put to the test, the designed robot structure demonstrated the main goal: to successfully move on off-road terrain and when an obstacle is encountered, to overcome it.
8. References

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