A hexapod robot for off-road applications

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Abstract. The present paper aims to approach aspects regarding the exploration of rough terrain areas using robotic systems. For a complete image on the approached subject (legged robots) several aspects are considered such as: determining stepping pattern for these types of robots, advantages resulting from designing such systems and the advantages resulting from the system’s large area of applicability. A hexapod robot with compliant legs has been designed, simulated, optimized and developed. The mechanical structure is different from a classical one as the two platforms are articulated one to the other. Compared to a classical structure where a turn is accomplished using different velocities for legs situated on opposite sides, in this case the turning is done by the relative rotation of the two platforms.

1. Introduction

Starting from the idea of developing a robot capable of moving on several types of surfaces the set objective was to develop a mechatronic system with such abilities. Existing documentation and research shows that legged robots have a high degree of mobility on such surfaces – a greater number of legs ensures a higher stability.

One of the more difficult problems is the structural schematics for the leg due to the complexity of the walking cinematics. There are several types of mechanisms which can be used for driving the leg, such as: mechanisms derived from the four-bar mechanism, pantograph type or more complicated mechanisms derived from cinematic chains with several independent contours [1]. The leg does not represent an element of continuous movement and must be lifted at the end of the run, turned and placed for the beginning of a new run.

The robot’s geometric parameters, shown in figure 1, are: the leg transfer phase represented by the time interval where the leg is now in contact with the ground (τ), the leg support phase represented by the time interval when the leg is in contact with the ground (C), the cycle duration (T) with a full movement cycle (T = C+τ). If the movement is periodical, then the cycle duration is the same for all legs.

The extreme positions of the support phase are the extreme anterior and extreme posterior positions. For a uniform rectilinear displacement for the robot in the support phase the leg’s extremity performs a motion opposite to the direction of movement. Also, in the transfer phase the leg advances to find a new point of support. For static stability at least three of the legs need to be in contact with the ground. For walking (displacement) to be considered continuous the usage factor need to be the same for all legs.
Different structures for stepping robots are presented below. The hexapod autonomous robot Szabad(ka) [2] developed by the Polyethnic „VTS“ in Subotica, in partnership with the Hungarian Academy of Sciences, for testing and creating movement algorithms, robotic vision, decision making and robot network connection. The hexapod robot Stiquito [3], build at the Indiana University, consists of a simple 6-legged structure driven using 6 actuators with nitinol wires. Another example is RHex [4], a hexapod robot developed by Boston Dynamics, similar to the one researched in the present paper. The last robot presented is a spherical 12-legged robot based on the rolling motion of the structure.

For most stepping robot structures ground contact is punctiform or limited and intermittent. For the structure to be developed there is the aim for an increased ground contact throughout the movement cycle. The shape of the leg was chosen to be a circle sector with a centre angle of about 300°.
By using this constructive solution for the leg, the objective is to obtain a uniform displacement for the robot as for the centre of mass positioning with respect to the ground level. The movement algorithm is defined by the sequential triangular displacement of the two groups of legs.

In order to decrease the turn radius, the robotic structure will consist of two jointed platforms around the OZ axis. For decreasing the overall dimensions, the layout of the central legs with respect to the other two framing them will be offset in such a manner that throughout a movement cycle they will not collide. It is desired that the robotics structure will be able to move on an inclined plane with an angle up to 30°.

2. Design of the hexapod robot
Considering stability problems encountered by wheeled robots when moving on damp or irregular terrains the compliant legged robot was designed to successfully handle movement in these types of situations. The shape for the legs was chosen following a study on arthropods movement and modelled so that it meets the flexibility requirement. The chassis shape and dimension were designed to keep the robot as compact as possible and to avoid leg inter crossing during stepping. The design solution with the overlapped platforms allows for the reduction of the overall dimensions and the inside positioning of the power source and some of the control electronics. This construction solution was chosen as the instruction of a joint in the middle area of the robot would have lead to an augmentation of the entire robotic system. Movement is sequential with two groups of 3 legs each with their rotation centres forming a triangle. This increases stability on several types of terrain and allows for passing obstacles that can be higher the robot’s ground clearance.

The chosen solution (shown in figure 3) represents a hexapod robot with compliant legs that eliminates movement problems on rough or wet terrain where classical legged or wheeled robots would have significant difficulties.

Focusing on the most reliable constructive solution, six servomotors are used for driving the legs. The proposed objective was to obtain a static stable robot; this involves permanent balance, so 3 legs are permanently in contact with the ground during movement. The robot with its main components is shown below: (1) the upper platform which ensures angular motion; (2) the lower platform which supports the structure when calibrating the angle between the two platform; (3) the servomotor; (4) element for fixing the servomotor on the platform; (5) element for fixing the leg on the motor; (6) compliant leg with the rotation axis perpendicular to the motor plane; (7) adherent surface for

![Figure 3. Compliant legs hexapod robot – concept.](image-url)
minimising leg slip on the ground; (8) fixing element for the servomotor ensuring angular movement to the lower platform; (9) fixing spacers for the central servomotor on the upper platform.

As the legs perform a continuous movement the servomotors had to be modified by eliminating the mechanic limitation and potentiometer. The central servomotor has not been modified as a good angular positioning of the two platform is necessary.

As shown in figure 3 the robot’s two platforms can move angularly one with respect to the other to perform required turns without using the mechanical structure.

Due to the shape of the motor shaft, grooved shaft, the connection part raised a series of problems. For optimal fixing of the leg to the driving element a solution with an elastic broach tightened with a screw was used (figure 5).

The legs are fixed to the motor shaft with a metallic attachment as shown in figure 5 with an interior grooved bore. The grooved interior represents the negative shape of the servomotor’s output shaft thus ensuring by tightening the screw optimal fixing for the leg throughout each step.

The leg is made from cold rolled steel sheet and fixes to the connection part using two screws. For increased grip on the ground contact area a pieced of toothed belt drive was attached.
The main advantage resulting from this solution is that it does not require workspace as for the classic hexapod robots. The workspace is defined as the surface occupied by a leg from the start to the end of a step. In this case the contact can be considered as a point as the point moves on the leg’s surface and not on the ground.

3. Simulation and optimization for the robot’s functioning

Adding all component to the CAD model, including the accumulator and the electronic board the position for the centre of mass was determined. With respect to the geometric centre it stands 12mm towards the front of the structure and 8 mm to the right; this means that the motor driving leg 6 is the most used due to the chosen displacement type – triangle. During a step the robot will be supported on three legs with the highest strain on the centre leg. Considering the centre of mass (a little off centred to the right) the right-hand side motor has the highest strain – motor for leg 6 as is shown in the figure below.

![Figure 6. Motor numbering.](image)

3.1. Robot modelling and simulation using MATLAB Simulink

As the contact point between the leg and the ground changes throughout a rotation, the length of the virtual leg \( l \) (shown in red in figure 7) changes. So, in a vertical position when \( \Phi=\pi \), the length becomes \( d \) (the rolling diameter for the leg).

![Figure 7. Robot leg length: a) in a vertical position; b) at an angle.](image)
Throughout the step this length decreases (figure 7 b). Considering OAB with the angle $\Phi$, and applying Pythagoras generalised theorem for the AOB triangle, we get:

$$
I^2 = \left(\frac{d}{2}\right)^2 + \left(\frac{d}{2}\right)^2 - 2 \cdot \cos \Phi \cdot \frac{d}{2} \cdot \frac{d}{2} = \frac{d^2}{2} \cdot (1 - \cos \Phi)
$$

(1)

From equation (1) we get the length of the virtual leg $l$:

$$
l = d \cdot \sqrt{\frac{1 - \cos \Phi}{2}}
$$

(2)

In figure 8 the functional schematic for a leg with the respective servomechanism is shown. Starting from the previously determined leg length and using values for the determined inertia moments and masses using the CAD model, a model for the leg was developed using MATLAB Simulink. The inertia moment for the reduction gear was reduced to the level of the motor shaft for simplifying purposes.

Figure 8. Simplified model for a leg.

The schematics below was done using the impedance network method. For this schematic using Kirchhoff network equations for the nodes and the branches between nodes the equations for the simulation schematics are written.

Figure 9. Impedance network.
3.2. Experimental results
The variation for the robot’s linear displacement can be observed by analysing the graphs shown in figure 10. When the leg is in contact with the surface the position increases and when the leg is in the air the displacement is 0. Velocity shown a similar behaviour as it increases at the time of contact and is 0 when the leg is in the air.

![Figure 10. Simulation results: a) linear displacement; b) linear velocity.](image)

3.3. Finite element analysis for the leg
With the CAD model for the leg and using a numeric techniques analysis software – Finite Element Analysis – SolidWorks - Simulation – we can study the leg’s behaviour at various positions. The table below shows the studied model and its characteristics.

![Figure 11. Equivalent Von Misses Strain.](image)

The material chosen is an AISI 304 steel with a load force of 5N, calculated as the robot’s weight distributed on this leg. Since during movement the robot stands on one leg on one side and two on the other the highest strain will be on the leg that support half of the robot’s weight. The force is applied in the first case on a leg section opposite to the joint with the angle from the vertical at 90°. In the second case the angle for the leg will be 45°.
The deformation for the leg is at about 2.5 mm for the first case and 0.05 mm for the second case. Both measurements for the deformation are taken at the leg’s point of contact with the ground. Form a mechanical resistance perspective the finite element analysis shows correct dimensioning for the leg; the factor of safety and the Von Mises strains both validate the dimensioning aspect.

![Figure 12. The leg displacement.](image)

4. Experimental setup

The electric schematics for the robot are presented in figure 13, we can observe: the mechanical limiters used for establishing the initial position for the legs, a Bluetooth HC05 adaptor and a 6-
channel level shifter, a Arduino Micro development board for ensuring control, seven servomotors grouped according to their position, the sensors – ultrasonic, temperature, humidity, sound detection and a photoresistor for measuring light intensity.

As the motors for the two platforms will not be driven at the same time they are grouped one form the upper and one from the lower platform – this allows for the usage of one regulator for two servomotors – there are 3 regulator subassemblies LM7806.

4.1. Driving algorithm for the legs

When stationary the robot has six support points and when moving it has three composing the vertices of a triangle as shown in figure 14. When moving the non-support legs are in the air at an angle of 180 degrees from the other three.

The main operations done by the robot are: bringing the legs to the zero position, performing a step and performing a turn. At the zero position three support legs forming a triangle are on the ground and the other three are rotated at 180 degrees.

![Figure 14. Driving of the motors: a) step 1; b) step 2.](image)

The figure 15 illustrates the logic al schematics for the main program. Communication with the robot is done by smartphone Bluetooth connection. Any application that can send a character to the Arduino microcontroller can be used; in this case a freeware application was used—Qwerty Bluetooth terminal. First the connection status is checked, if there is a connection the receival of a character is expected if not a message will be sent to the user.

The program is designed so that the first step is always the check subroutine – this involves checking the zero positions. First the inputs from the push buttons are read; if these are not pressed that means the respective leg is not in the zero position – the respective leg will be driven until the button is pressed.

The „Forward” subroutine always starts with the legs in the zero position. For this the buttons were placed in such a manner that the legs from the upper platform will be in the air and the others will be in contact with the ground. If one of the legs is not in the reference position they will not be synced, and this will result in a nonlinear displacement. For the next step all legs will be driven simultaneously, they will be driven until the buttons are again pressed – this represent the forward step.
Similar to the previous subroutine a turn can be accomplished. With the difference being that simultaneous to the driving of the legs also the central motor will be driven with the appropriate angle for the turn. If it steers right there will be an angle of $45^\circ$ and for a left steer the angle will be $-45^\circ$. When the step is finished the platform will return to the reference position.

4.2. The first prototype

Figure 15. Logic diagram of the main program.

![Logic diagram of the main program.](image)

Figure 16. The first prototype of hexapod robot.
In figure 16 the first prototype of the project is presented. The hexapod robot was successfully tested in different conditions; the robot can overcome small obstacles and can climb slopes up to 30°. Due to the shape of the legs and intermittent contact an oscillating vertical movement of the structure can appear. If the speed of the legs actuators is high enough, the amplitude of this oscillating move can be diminished.

5. Conclusions
Legged robots offer some significant advantages compared to wheeled robots: they can move on rough terrains with potholes and overcome obstacles of significant height; they also have some extreme abilities such as climbing on vertical surfaces.

Starting from the idea of developing a robot capable on moving on a rough terrain a functional model for a hexapod robot with compliant legs was designed, modelled, simulated, optimised and constructed.

Compared to existing structures for such robots the proposed solution has the advantage of being able to accomplish a turn in much smaller perimeters since the structure is comprised of two jointed platforms in the robot’s geometric centre.

The legs shape, a circle arc fixed at one end give the robot great elasticity for absorbing small surface unevenness.

6. References
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