Design of a versatile inspection mobile robot with drilling module for space applications

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Abstract

This paper presents a design of a versatile tracked inspection mobile robot with an adjustable drive positioning system equipped with a drilling module for space and terrestrial applications. The robot is intended to operate on open terrain and in enclosed space. Track position adaptation mechanism enables the robot to work on uneven surfaces. A concept of utilization of a lightweight core drilling module for soil specimen collection is presented. Kinematic and dynamic models are outlined, along with simulation and experimental verification of a prototype.

Keywords: Mobile robot; drilling; inspection; space; tracked vehicle; core drill; dynamic model

1. Introduction

Inspection is a popular application field of mobile robots. Usually, these devices are used in harsh environments or unreachable places for humans. We may distinguish inspection robots dedicated for military applications, storage tanks, high voltage cables or pipelines [1]. These devices utilize various means of data collection, including CCTV cameras, NDT sensors or other inspection equipment. Mobile robots may be also utilized for collection of specimens. In this paper a design of an inspection robot with drilling module is presented. It is intended for operation in extreme environments such as space missions or remote places on Earth. The main drilling unit features a core drill bit with soil or rock specimen collection capabilities.

Soil and rock specimen collection has been a research field for many years because extraction of samples is one of the most important tasks of space missions. Many drilling mobile systems has been designed, yet collection of deeply situated specimens is still an issue to research. There is a hypothesis that extraterrestrial bacteria species may exist in lower layers of ground. One of the most successful devices that were utilized is Apollo Lunar Surface Drill [2]. This device that possessed power exceeding 450 W was utilized to make holes up to 3 m deep. Nevertheless, the device was operated by astronauts. The deepest hole produced by an unmanned drill was done on the Moon, where Luna 16 robotic probe managed to collect specimen from 350 mm depth [3]. As we may observe the depth was usually low according to [2]. Laboratory tests for deep drilling were performed by several research team. The system presented in [4] has the potential to drill a hole up to 2 m, however the size is significantly bigger.

In this paper a mobile drilling robot with an advanced hole protection system is presented. The mobile platform can adapt to various work environments. It is based on two track modules with integrated motors, mounted on a positioning structure, consisting of three drives per track. The robot possesses ability to operate on flat and uneven surfaces and in enclosed space. It can be also utilized for inspection of pipelines and ducts as presented in [5].

There already exist many other designs of mobile inspection robots, but the majority of them possess low level of adaptivity to the operating environment. A tracked inspection robot for operation in changeable conditions is presented by Tadakuma et al. [6]. They proposed a platform with a cylindrical track drive - Omni-Track that increases the contact area with curved surfaces and allow forward and backward motions along with a side motion, realized by a roll mechanism. Versatrax tracked inspection robots produced by Inuktun feature manually adjustable tracked platforms for pipeline inspection [7]. iPEK produces wheeled inspection vehicles, ROVVER for pipes with various diameters that may also be utilized for inspection of open space [8]. These robots have modular designs, with replaceable wheels, but are dedicated to particular pipelines. Space rovers such as Curiosity [9] are usually much bigger and intended for more complicated tasks including specimen collection and vision surveillance, although may not be used for penetration of enclosed space and tight passages.

As we may observe, various inspection robots are utilized for different purposes. Wheels are energy efficient, but provide small contact surface resulting in lower traction. Tracks provide high mobility in changeable conditions due to considerably large contact area with the surface. In this work, a versatile tracked mobile robot is presented that is intended for core drilling and sample collection or inspection of enclosed space with utilization of a camera. In contrast to the devices available on the market or presented by other research teams, the mobile platform may be automatically adjusted to adapt to work environment, whilst the other can only be used for a specific task. In this paper an adaptive track positioning...
system that ensures maximum versatility of the mobile platform is described. Mathematical models are formulated and validated and drilling operation is described.

2. Mechanical structure of the mobile platform

The mobile robot consists of two tracks that serve a function of main drives. For this project, Inuktun Microtrac track modules with dimensions 60x50x170 mm are utilized. Additionally, the mobile platform is equipped with a positioning system of track drives that enables adaptation to work environment. For creation of the virtual prototype of the inspection robot, Autodesk Inventor Professional 2012 software was used [5].

The track positioning system consists of two independently rotating rings, with a centre of rotation in the axis of the robot body (Figure 1). To each of these rings, an arm is attached on a rotary joint. These arms are similarly mounted to both sides of each track. This configuration allows various orientations of the tracks with respect to the robot body [5]. Each track unit is adjusted by three drives. Two drives allow rotations of rings with respect to the robot body axis and the third drive positions one arm with respect to the track. The drives selected for the rotating rings are digital servomotors Hitec HS-7950TH that are compact size, possess high holding torque and an integrated position controller. The rotating rings are connected with the robot outer and inner arms. The general view of the robot is presented in Figure 1. The drive controllers and power electronics are located inside of the robot body.

In total, the robot has 8 drives: 2 tracks and 6 track positioning servomotors. It may be supplied by wire or wireless. The wireless operation requires installation of an additional battery and gives 15 minutes of operation at this design stage. Future development of additional power source is necessary for longer tasks.

3. Mathematical modeling of the robot

Mathematical modeling of the robot was performed in order to design a control algorithm and optimize motion for flat and inclined surfaces. A forward kinematic model was created from which forward and inverse dynamic models were derived.

3.1 Kinematic model

Kinematic model was derived in order to determine velocities of tracks for a given trajectory of the robot, thus, enable control of position and orientation. In a simplified model, elastomeric tracks with treads are modeled as a non-stretch tape wound about a determined shape by a drive sprocket, an idler and an undeformable ground [10, 11, 12]. The presented kinematic model of the robot describes a plane motion (Figure 2) and an operation on inclined surfaces.

To calculate the velocity of point C (Figure 2), placed in the axis of symmetry of the crawler, [12, 13] we have to take into consideration slip of track (equation 1). The velocity components in coordinate system and angular velocity of the point C is presented in equation 2.

\[
S = \frac{(n-1)dL}{L} \tag{1}
\]

\[
\begin{align*}
\dot{x}_C &= \frac{r \dot{\alpha}_1 (1 - s_1) + r \dot{\alpha}_2 (1 - s_2)}{2} \\
\dot{y}_C &= \frac{r \dot{\alpha}_1 (1 - s_1) + r \dot{\alpha}_2 (1 - s_2)}{2} \\
\dot{z}_C &= \frac{r \dot{\alpha}_2 (1 - s_2) - r \dot{\alpha}_1 (1 - s_1)}{H} \\
\dot{\beta} &= \frac{r \dot{\alpha}_2 (1 - s_2) - r \dot{\alpha}_1 (1 - s_1)}{H} \sin \beta
\end{align*} \tag{2}
\]

where: \(n\) - number of track treads in contact with the ground, \(dL\) - track tread deformation, \(L\) - length of a track load bearing segment.

\(r\) - radius of the track drive sprockets, \(H\) - distance between the tracks, \(s_1\) - slip of the sprocket 1, \(s_2\) - slip of the sprocket 2, \(G\) - gravity force, \(\eta\) - efficiency, \(\dot{\alpha}_1\) - angular velocity of the sprocket 1, \(\dot{\alpha}_2\) - angular velocity of the sprocket 2, \(\beta\) - the angle of slope inclination

3.2 Dynamic model

The dynamic description of the robot [12, 14] was prepared using an energetic method based on the Lagrange equations. Forward dynamics problem was solved to determine accelerations of track drives for given torques of electrical
motors and inverse problem was derived to calculate required torque of electric motors for a given trajectory. In order to avoid modeling problems with decoupling Lagrange multipliers, the Maggi’s equations were used \[15\]. In the dynamic model of the robot, the same characteristic points on the structure are considered as in the kinematic description. Figure 3. shows a side view of the mobile platform on an inclined surface with track components used in the simplified model.

![Figure 3. Dynamic model of the robot - forces; 1 - sprocket, 2 and 3 - idlers](image)

It has to be assumed that the kinetic energy of the robot \( E \) is the sum of energies of particular components:

\[ E = E_R + E_{M1} + E_{M2} \]  

(3)

where: \( E_R \) – kinetic energy of the robot frame, \( E_{M1} \) – kinetic energy of the left track drive module, \( E_{M2} \) – kinetic energy of the right track drive module

The kinetic energy of the robot frame is the sum of energies \( E_{R1} \) and \( E_{R2} \), resultant from translational and rotational motions with respect to the instantaneous center of rotation \( O \).

\[ E_R = E_{R1} + E_{R2} = \frac{1}{2} m_R (\dot{x}_c^2 + \dot{y}_c^2 + \dot{z}_c^2) + \frac{1}{2} I_R \beta^2 \]  

(4)

where: \( m_R \) – mass of the robot frame, \( I_R \) – moment of inertia of the robot frame, \( \beta \) – angular velocity of the robot frame with respect to the instantaneous center of rotation

In equation 5 kinetic energies of the left and right track drive modules are described after substitution of velocities denoted in equation 2 according to the notation in equation 3.

\[ E_{M1} = \frac{1}{2} m \left( (\dot{x}_c - \beta H \sin \beta)^2 + (\dot{y}_c - \beta H \cos \beta)^2 + \dot{z}_c^2 \right) + \frac{1}{2} I_s \dot{a}_2^2 + \frac{1}{2} I_r \beta^2 \]  

\[ E_{M2} = \frac{1}{2} m \left( (\dot{x}_c + \beta H \sin \beta)^2 + (\dot{y}_c + \beta H \cos \beta)^2 + \dot{z}_c^2 \right) + \frac{1}{2} I_s \dot{a}_2^2 + \frac{1}{2} I_r \beta^2 \]  

(5)

The total kinetic energy of the robot described in equation 6. It was derived with usage of equation 4 and equation 5:

\[ E = \frac{1}{2} m_R (\dot{x}_c^2 + \dot{y}_c^2 + \dot{z}_c^2) + \frac{1}{2} I_R \beta^2 + \frac{1}{2} m \left( (\dot{x}_c - \beta H \sin \beta)^2 + (\dot{y}_c - \beta H \cos \beta)^2 + \dot{z}_c^2 \right) + \frac{1}{2} I_s \dot{a}_2^2 + \frac{1}{2} I_r \beta^2 \]  

(6)

In order to solve inverse and forward dynamics problems, the Maggi’s formalism was utilized:

\[ \sum_{j=1}^{n} C_{ij} \left[ \frac{d}{dt} \left( \frac{\partial \theta_i}{\partial q_j} \right) - \left( \frac{\partial \phi_i}{\partial q_j} \right) \right] = \theta_i \]  

(7)

where: \( n \) – the number of independent parameters expressed in generalized coordinates \( q_i \) (\( j = 1, ..., n \)), \( \theta \) = \( [\dot{\alpha}_1, \dot{\alpha}_2]^T \), \( G_j = [0 \ 0 \ 0 \ 0 \ 0 \ 0]^T \)

According to this assumption, six generalized velocities were denoted by multiplication of the matrix \( C_{ij} \), that consists of nonholonomic constraints with two kinematic parameters \( \dot{\alpha}_1, \dot{\alpha}_2 \).

\[ \begin{bmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{z}_c \\ \dot{\alpha}_1 \\ \dot{\alpha}_2 \end{bmatrix} = \begin{bmatrix} r(1-s_1) \sin \beta & r(1-s_2) \sin \beta \\ \frac{1}{2} r(1-s_1) \cos \beta \cos \psi & \frac{1}{2} r(1-s_2) \cos \beta \cos \psi \\ \frac{1}{2} r(1-s_1) \sin \psi & \frac{1}{2} r(1-s_2) \sin \psi \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\alpha}_1 \\ \dot{\alpha}_2 \end{bmatrix} \]  

(8)

The generalized forces and moments are denoted using equation 9:

\[ \begin{bmatrix} m_n1 + (-0.5P_u - 0.5P_d - 0.5G \sin \psi + 0.5F \sin \psi) \\ M_{n1} + (-0.5W_{11} \rho(1-s_1) + M_{p} \rho(1-s_1)) \end{bmatrix} \]  

\[ \begin{bmatrix} m_n2 + (-0.5P_u - 0.5P_d - 0.5G \sin \psi + 0.5F \sin \psi) \\ M_{n2} + (-0.5W_{12} \rho(1-s_2) - M_{p} \rho(1-s_2)) \end{bmatrix} \]  

(9)

The final form of the dynamic motion equations based on the Maggi’s formalism have been derived for inverse dynamics (equation 10) and forward dynamics (equation 11).

\[ \begin{bmatrix} m_n1 + (-0.5P_u - 0.5P_d - 0.5G \sin \psi + 0.5F \sin \psi) \\ M_{n1} + (-0.5W_{11} \rho(1-s_1) + M_{p} \rho(1-s_1)) \end{bmatrix} \]  

\[ \begin{bmatrix} m_n2 + (-0.5P_u - 0.5P_d - 0.5G \sin \psi + 0.5F \sin \psi) \\ M_{n2} + (-0.5W_{12} \rho(1-s_2) - M_{p} \rho(1-s_2)) \end{bmatrix} \]  

(10)
To make the equations more readable, coefficients were introduced. They are denoted by equation 12:

\[
\begin{aligned}
\alpha_1 &= (a_2 b_2 \alpha_1^2 - a_3 b_1 \alpha_1^2 + a_1 b_1 \alpha_1^2 + \alpha_3 b_3 - a_3 b_2 + a_3 M_{a_2} - b_2 M_{a_1})/(a_2 b_3 - a_3 b_2) \\
\alpha_2 &= (a_2 b_2 \alpha_2^2 - a_3 b_1 \alpha_2^2 + a_1 b_1 \alpha_2^2 + \alpha_3 b_3 - a_3 b_2 + a_3 M_{a_2} - b_2 M_{a_1})/(a_2 b_3 - a_3 b_2) \\
\alpha_3 &= (1/4) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) (1 - s_1) \\
&+ (1/2) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) (1 - s_1) - r^2 (I_R + 2l_z + 2mH^2) (1 - s_1)/H^2 \\
\alpha_4 &= (1/4) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) + \\
&+ (1/2) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) + \\
&+ r^2 (I_R + 2l_z + 2mH^2) (1 - s_1)/H^2 \\
\alpha_5 &= r (1 - s_1) \left[ 0.5 F_w \sin(\gamma) - W_{t_1} - 0.5 P_D - 0.5 F_D - 0.5 G \sin(\gamma) \right] + \frac{M_p (1 - s_1)}{H} \\
\beta_1 &= r^2 (1 - s_2) \cos(\beta) (m_R + 2m) \sin(\beta)/4H - \\
&- r^3 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) \cos(\beta)/4H \\
\beta_2 &= r^2 (1 - s_2) \cos(\beta) (m_R + 2m) (1 - s_2) \sin(\beta)/4H + r^3 \\
&- r^3 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) (1 - s_2) \cos(\beta)/4H \\
\beta_3 &= (1/4) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) + \\
&+ (1/2) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) + \\
&+ r^2 (I_R + 2l_z + 2mH^2)/H^2 + l_x \\
\beta_4 &= (1/4) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) (1 - s_1) + \\
&+ (1/2) r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) (1 - s_1) + \\
&+ r^2 (1 - s_2) \sin(\beta) \cos(\gamma) (m_R + 2m) (1 - s_1) - \\
&- r^2 (I_R + 2l_z + 2mH^2) (1 - s_1)/H^2 \\
\beta_5 &= r (1 - s_2) F_w \sin(\gamma)/2 - W_{t_2} - P_T/2 - F_D/2 - \\
&- G \sin(\gamma)/2 - M_p (1 - s_2)/H \\
\end{aligned}
\]

When utilizing the inverse and forward dynamics equations 10 and 11 care must be taken in terms of environment-dependent force values such as $W_r$ since various surfaces on which the robot operates would introduce significant variations in its value [16]. The type fluid in which the robot moves has also a strong influence on the forces, especially $F_D$ and $M_p$.

3.3 Validation of mathematical models

In order to validate forward and inverse dynamics of the mobile platform, a laboratory test of the prototype was conducted. Next, a Matlab Simulink model was prepared and simulated.

Data used in the simulation:

\[
\begin{align*}
  r &= 0.02794 m, H = 0.12 m, s_1 &= s_2 = 0.011, \\
  P_u &= 10 N, m &= 1.1 kg, m_R = 3.04 kg, \\
  G &= 51.404 N, I_R &= 0.0194 kg \cdot m^2, I_z &= 0.000651 kg \cdot m^2, \\
  F_w &= 18.639 N, \gamma &= 0^o, \beta = 0^o
\end{align*}
\]

Results for linear trajectory are presented in Figure 5. and Figure 6. We may observe that the calculated velocity and torques coincide considerably well to the measurements conducted on the test stand. It may be concluded that the dynamic model of the robot can be utilized for control algorithm of a prototype.

4. Pipeline inspection

The mobile platform presented in this paper may be utilized for inspection of enclosed space such as pipelines. The robot is
capable of positioning its driving mechanism in various ways to adapt to work environment. In Figure 7. a) a prototype of the robot is depicted in a horizontal pipe Ø235 mm. The upper limit of pipe diameter is determined by the capabilities of the vision system. For the most compact alignment, the prototype is able to operate in pipes Ø210 mm. Inspection of tight enclosed space such as vertical pipe is presented in Figure 7. b).

The robot may also work in pipes and ducts with a rectangular cross-section. The same position is utilized for inspection of flat surfaces or collection of samples using a drilling module.

5. Drilling module

To collect soil or rock specimens it is necessary to attach a drilling module to the mobile platform presented in the previous sections. The main structure is depicted in Figure 8. It consists of a 16 mm diameter core drill bit with a specimen container. It is mounted to a planetary gearbox with an electric motor. The entire assembly is guided to the hole by a coilable tape wound about a drum that after unwinding produces a tube with high compressive and bending strength. The drilling module is mounted on an extendable frame that consists of two actuated arms with guides. Additionally, when the drilling module starts to advance down into a hole, a protection coilable tape is pushed downwards to prevent collapse of hole walls during drilling and when the drill bit is taken out.

When the drill bit core fills completely with soil or rock, there is a latching mechanism on the top of the inner tube that prevents losing a specimen. When collection of deeply located layers of rock is required, it is necessary to withdraw the drilling module from the hole and remove soil by releasing the latch mechanism. Next, the drill bit needs to be inserted again into the hole.

For this structure, it was assumed that only one specimen may be carried by the mobile robot, latched inside of the drill bit. Hole depth is limited by coilable tape lengths that do not exceed 2 m for this design, power of motor, rock type and power supply.

Laboratory tests were performed to select an appropriate drilling bit. As a result of these experiments, a two-step four insert core drill bit was proved to be the most effective tool for electric motor with power not exceeding 100 W. The inserts are made of hardened steel, which in contrast to e.g. diamond inserts is less abrasion resistant, however it offers better performance in nonhomogeneous material as rocks that may be encountered during drilling. Diamond inserts may fracture when a drill bit encounters a hard portion of rock. For the available motor power it is possible to drill in rocks with strength not exceeding typical values for chalk or weak claystone. Performance of the drilling module equipped with a coilable tape was verified in laboratory for the depth of 500 mm.

6. Drilling operation

The mobile platform presented in previous sections is capable of transporting the drilling module in different environments. To provide the highest level of mobility, it was decided to maintain possibility to transport the drilling module in a compact position (Figure 9 a) and expand it only for drilling (Figure 9 b). By realization of this approach the mobile platform provides access to tight places like river beds or niches unlike a standard not adjustable wheeled robot.

To optimize stability of the robot during operation, center of gravity of the mobile platform was shifted backwards, thus with the drilling module extended it is in the middle of tracks.
In Figure 10, a concept of drilling operation is presented. We may observe that in Figure 10, a) the robot is moving on a horizontal surface, whereas in Figure 10, b) an operation on a curved surface is presented. Drive adaptation may also be utilized to stabilize the structure for drilling (Figure 10 b).

7. Conclusions

This paper describes a versatile mobile inspection robot that may be utilized for various types of inspection and soil specimen collection. A 3D model was prepared using CAD/CAE tools and a prototype was built. Kinematic and dynamic mathematical models of the robot were formulated and verified experimentally. An innovative mobile drill module intended for terrestrial and space applications was proposed as a component of the mobile platform. Because of its small size, the system can be utilized in enclosed space and in harsh environment with limited access. Mobile platform and drilling module equipped with a coilable tape were tested as functional subsystems of the robot. It may be concluded that the proposed device is well suited for specimen collection and inspection tasks when weight and mobility is an important factor because the place in not easily accessible by larger devices.

8. Further work

The designed drilling module has to be manufactured and tested as an entire system with the mobile platform. Performance of particular components of the drilling module was proved to be adequate, however interaction with the mobile platform must be taken into account. Tests of the entire system should be conducted in conditions corresponding to terrestrial or space environment in which the robot is intended to operate.

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