Structure design of a miniature and jumping robot for search and rescue

Xueying Wang1, Xiaojing Yang1
1 Kunming University of Science and Technology, Kunming, People’s Republic of China
E-mail: 148425509@qq.com

Abstract: The extremely dangerous and complex environment caused by tremendous earthquakes or unnatural disasters usually brings great danger to survivors and salvagers. Therefore, search and rescue missions after any disaster indicate a huge need in special access to reduce the loss for human beings and, at the same time, to improve the capability of performing the tasks. In terms of the miniature robots which can go into the confined zone for the searching tasks, this project focuses specially on analysing climbing obstacle capability of the miniature robots, and introduces a new concept composed of a jumping robot which is mounted on a tracked mobile base. To design, calculate, and analyse this system, an appropriate mechanism, geometric dimensions, and specific properties are detailed, which include a dual-tracked articulated transformable locomotion system, a transmission system with a sleeve shaft, an incomplete gear jumping mechanism, and the selection and calculation of power system motors. To complete the design procedure, a three-dimensional sketch of each component of the robot was generated by means of Solidworks.

1 Introduction

The robot designed, named M-bot in this paper, takes size and configuration fully into account to fit the destructed areas post seismic. Size is a critical factor for disaster-relief robots, in which volume and weight of M-bot are set as $(2.86 \times 10^{-3})$ m$^3$ and 2 kg, respectively, to enhance the advantage of accessing parochial spaces. On the other hand, for keeping the high level of obstacle detouring capability, the adapted classical shape-shifting tracked configuration is adapted. The articulated design can adjust shape to accommodate different terrains while overcoming barriers and providing the take-off angle appropriately. Another highlight of M-bot is the jumping function which can solve the problem caused by small size. In general, the robot could not surmount obstacles which are higher than 2/3 times its own height. It is undeniable that jumping is a commendable way to tackle this problem favourably for small robots; thus, a pair of incomplete gear mechanism [1] assists the accumulation and liberation of spring energy to accomplish jumping performance in this design.

2 Methodology

2.1 Overview of design

On the whole, M-bot is a miniature robot based on the integration of a crawler robot and a jumping robot; the robot is constitutive of the crawler-type travel mechanism, flipper rotation mechanism, and jumping mechanism chiefly. Fig. 1 depicts the graph of a Solidworks model of M-bot.

M-bot is a good delegate with articulating front flipper tracks; its dual-tracked system serves as the basic locomotion structure for enhanced mobility. This type of structure is consisted of two-part tracks. Tracks which are driven by two stand-alone motors on each side are the main steering tracks. The main tracks function is supporting actions such as straight line walking, swerve, climbing and obstacle detouring with normal conditions. The motor located in the middle of the body controls the rotation of the other tracks; the arms of the robot change its shape when it meets obstacles and prepare it for jumping as required.

A sleeve shaft structure is used to separate the rotation of arms and running of the track. The jumping system is composed of a pair of rack, half-gear, and two springs. The rack and half-gear play the role in compressing and releasing the energy-storage system which actually is the spring system, the most efficient and simplest energy-storage intermediary.

Table 1 lists the main predetermined parameters of a robot. The power source is a swing battery from Boston-Power's [2], which is a rechargeable lithium-ion cell. This battery has been selected to power the National Aeronautics and Space Administration's (NASA's) human-like robot project due to its capability of a wide range of transportation, utility energy density, and long reliable life. Each cell outputs a nominal 3.7 V at 4400 mAh, two cells could be installed in series to meet the motors' nominal 6 V. The high nominal capacity can support the robot work over 25 h.

| Table 1 | Main specifications of M-bot |
|---------|-----------------------------|
| weight  | 2 kg                        |
| length × width × height | $188 \times 186 \times 82$ (mm$^3$) |
| diameter of drive wheel | 63 mm                     |
| diameter of front wheel | 32.5 mm                   |
| length of flipper    | 100 mm                     |
| maximum velocity    | 0.25 m/s                   |
| maximum jumping height | 28 cm                     |
| maximum jumping distance | 51 cm                     |

Fig. 1 Final model of M-bot
2.2 Mechanical design

2.2.1 Locomotion mechanism: The double-tracked system was elected finally. The main tracks take responsibility of the usual march, whereas another pair of tracks are used for transformation to meet different missions. M-bot is a jumping robot but with a very rigid structure, which will increase the risk of damage at landing time, and the robot's body even breaks down under serious conditions. A safe landing is desired after the robot jumps from a high position, and an ingenious modification of wheels is designed to reduce the impact force when the robot landing is at a certain extent. A spring-suspension mechanism is placed as umbrella ribs within wheels [3].

2.2.2 Motor arrangement: There are four sets of motor and relevant gearhead in all. Two sets for driving the front wheels in main tracks are the only power source for the whole robot: one for the control of flippers and the other one is used to achieve the jumping mechanism. In order to maximise the save of space, all of the components in the body should be arranged reasonably, especially for the motors and reducers which would occupy the most room inside. A well distribution can save enough space for further components such as sensors, cameras, controller modules, and so on. On the other hand, the robot weight could be balanced much better. The robot performance is highly possible to be influenced by the installation sites, installation accuracy, and the strength of fixed plates. Too much use of the noisy and fierce shocks would emerge seriously with bad installation accuracy, and what is worse is that the appearances locked dead in the consequence of the motor destroyed. In accordance with the small size of the robot and the profile and dimension of motors, the first three sets of the motor and gearbox would be put together side by side in the front area of the body as the horizontal arrangement type are selected as shown in Fig. 2.

The main tracks adopt independent drive to realise differential steering, and the torque and velocity needed for the whole vehicle rotation are supplied by the two driven motors. Both the running speed and rotation angular velocity could be controlled through adjusting the differential speed of driving wheels, and then the robot can move forward and backward or rotate according to the radius of curvature and pivot steering, following the required direction and velocity. The driving motors are located at each side separately next to the tracks (see Fig. 2).

For flippers' motor, considering the two flippers should rotate simultaneously, only one motor is used rather than locating every motor on each flipper separately. Also, the power would be supplied via a pair of bevel gears which connect the two drivetrains of flippers.

2.2.3 Transmission system: The main power driveline is characterised by a simple and compact structure with high transmission efficiency. The process is that driving power from motor goes through the gearbox with a desirable ratio, then a pair of bevel gear which connects the out shaft of the gearbox and that of the driving wheel changes the direction of transmission motion, and then the power is delivered to the main moving wheel via bevel gears; another follower wheel is driven by the track (see Fig. 3).

How to isolate transforming and moving is a key issue for the transformable crawler robot. The main driveline and flipper driveline possess the same physical geometry centre of circle but different circumferences, which would bring about the trouble of the working interference to each other – whether synchronised or independent. In this case, a special separated type is designed – sleeve shaft. The shaft inside controls the rotation of the flipper, and the outer big shaft is responsible to keep the robot moving. These two actions can be achieved separately without affecting one another, and the power system of the robot can be centralised much more. From another point of view, space utilisation, the transform performance, and manoeuvring characteristics are improved greatly. Two flippers share one power source via a pair of bevel gears, which makes the arms change position synchronously. The power and rotation would transfer to the linkage between two wheels in flippers through the inside shafts, and the rotation and torque of the linkage would drive the whole arm pivoting (see Fig. 4).

2.2.4 Jumping mechanism: An intermittent mechanism – with an incomplete gear and a rack – was conducted as the key point to realise the energy storage and liberation in springs. An incomplete gear is a gear with its teeth at only half-circle. As a result, the meshing between the gear and rack is restricted in this semi-circle. The springs are fixed in the middle of the body along with two guided rods, in which the rack contacts the other end of springs, similar to the role of the shim plate in the previous design (see Fig. 5).

During the rotation within 0–180°, springs are in elastic potential energy-storage situation. The incomplete gear meshing with the rack, then the rotary motion of pinion converses to linear motion of the rack. Therefore, movement of the rack compresses the springs while mechanical energy transforms into elastic energy of springs via reducer, pinion and rack. As the instant of the last tooth of the pinion detaches away from the rack, springs get transient liberation so as to supply adequate energy for the robot jumping. Then at the rest, at 180°, the incomplete gear and the rack...
remain in the unloading state. Through this whole process, the robot can perform jumping motion (see Fig. 6).

With the jumping height \( h \), take-off angle \( \alpha \), take-off velocity \( v_0 \), horizontal velocity \( x(t) \), and vertical velocity \( y(t) \) during flight on the top of the jumping trajectory \( v_{top} \), the spring potential energy is given by

\[
E = \frac{1}{2}K\Delta x^2 \cdot 2 = \frac{1}{2} \times 7000 \text{N/m} \times (0.02827 \text{m})^2 \times 2 = 5.59 \text{J}
\]

where the spring compressed length = rack stroke = half-perimeter of the incomplete gear:

\[
18 \text{mm} \times \frac{3.141}{2} = 28.27 \text{mm}
\]

The jumping height and the jumping distance [4] can be estimated as

\[
h = \frac{E}{mg} = \frac{5.59 \text{J}}{2 \text{kg} \times 9.81 \text{kg/N}} = 0.28 \text{m}
\]

\[
d = \frac{2E\sin 2\alpha}{mg} = \frac{2 \times 5.59 \text{J} \times \sin 65}{2 \text{kg} \times 9.81 \text{kg/N}} = 0.51 \text{m}
\]

This corresponds to an initial take-off \( v_0 \):

\[
E = \frac{1}{2} \cdot m v_0^2 = 5.59 \text{J}
\]

\[
v_0 = 5.59 \text{m/s}
\]

Based on the ballistic jump kinematics [5, 6], the force balance on the system during jump (Fig. 7) can be expressed as

\[
F_a(t) = - F_{air}(t) \cdot \cos(\alpha)
\]

\[
F_r(t) = - F_{air}(t) \cdot \sin(\alpha) - G
\]

where \( F_a(t) \) is the horizontal and \( F_r(t) \) is the vertical force, \( G \) is the weight, \( F_{air}(t) \) is the air friction, and \( \alpha \) is the angle of the flight direction. As a first model of the air-friction force, \( F_{air}(t) \), we assume the following:

\[
F_{air}(t) = \frac{1}{2} \rho v^2(t) A_{cd}
\]

with \( \rho \) being the air density, \( x(t) \) the velocity of the system, \( A \) the frontal area, and \( cd \) the drag coefficient.

We obtain a system of two nonlinear second-order differential equations with \( x(t) \) being the horizontal velocity and \( y(t) \) the vertical velocity. Accordingly, \( \dot{x}(t) \) is the horizontal acceleration and \( \dot{y}(t) \) is the vertical acceleration:

\[
\dot{x}(t) = - \frac{1}{2m} \rho A_{cd} \cos \alpha \cdot \left[ \dot{x}(t) + y^2(t) \right]
\]

\[
\dot{y}(t) = - \frac{1}{2m} \left[ 2g + \rho A_{cd} \sin \alpha \cdot \left[ \dot{x}(t) + y^2(t) \right] \right]
\]

However, the frontal area \( A \) and the drag coefficient \( cd \) are not known exactly, a priori, and have to be estimated. The fact that M-bot can be modelled as a one jumping animal-locust allows us to adopt data from animal studies to provide a first approximation. We model the robot as a cylindrical body (length \( l \) of 188 mm and diameter \( d \) of 80 mm), as suggested by Bennet-Clark and used for locusts. Assuming the flight direction in line with the body axis, a take-off angle \( \alpha \) of 30°, a friction coefficient \( cd \) of 1.3, and an air density \( \rho \) of 1.2 kg/m³ [7], the equation can be expressed as

\[
x(t) = -2.65 \times 10^{-5} \cdot \left[ \dot{x}(t) + y^2(t) \right]
\]

\[
y(t) = -24.06 - 2.34 \times 10^{-5} \cdot \left[ \dot{x}(t) + y^2(t) \right]
\]

If making \( [x(t)]^2 + [y(t)]^2 \), then equation can be converted to:

\[
a^2 = 9.37 \times 10^{-6} \cdot (v_0^2) + 0.015 \cdot (v_0)^2 + 24.06
\]

when \( v_0 = 5.59 \text{ m/s} \), the acceleration \( a \) is equal to \( 4.9 \text{ m/s}^2 \).

3 Results

A novel jumping mechanism of the incomplete gear and rack with springs was exploited. According to mathematic calculation, the small robot can jump to 28 cm at \( x \) component and 50 cm at \( y \) component. A sleeve shaft structure was used to solve the rotational concentric problem of arms and main tracks, in which the two arms can rotate around 360° in order to assist the robot in fulfilling sorts of transformation activities. Through the change of angular of arms and posture of the robot, M-bot can overcome varying degree obstacles, climbing or jumping over directly, and enforce greatly the obstacle-climbing capability. Furthermore, the mini size with a volume of 188 × 186 × 82 mm³ perfects the manoeuvrability of the robot, which pushes the robot back into the tight space freely and helps accomplish the search task.

3.1 Kinematic analysis

3.1.1 Kinematic analysis of flipper position: The transformable robot works as the typical tracked vehicle without opened arms. Assuming that the ground bearing distribution of vehicles on rubber tracks is average, the \( XOY \) coordinate frames are assigned for two tracked motion modes (see Fig. 7).

Muir and Newman [8, 9] developed a mobile robot Jacobian to express the relationship between position and velocity:

\[
v = J \cdot v_n
\]

\[
= (v_x, v_y, v_w)^T
\]

\[
= \text{instantaneous velocity of the robot whith respect to the coincident floor frame}
\]

Then, we can obtain

\[
\begin{bmatrix}
\dot{v}_x \\
\dot{v}_y \\
\dot{w}
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{2} \cos \theta & \frac{1}{2} \sin \theta & 0 \\
\frac{1}{2} \sin \theta & -\frac{1}{2} \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\dot{v}_x \\
\dot{v}_y \\
\dot{w}
\end{bmatrix}
\]

where \( v_x \) and \( v_y \) are the \( x \) and \( y \) components of robot velocity, respectively, and \( w \) is the angular velocity of the robot.

3.1.2 Kinematic analysis of flipper position: The joint of robot arms is regarded as a one-link manipulator, which can be analysed using the forward kinematic algorithm. The articulation is moved to assign a coordinate frame at its zero position. The forward kinematic algorithm is to represent the homogeneous transformation between joints with \( A \) matrices [8] (see Fig. 8):

\[
A_n = \text{Rot}(0, 0, d) \text{Trans}(l, 0, 0) \text{Rot}(x, \alpha)
\]
Substituting these parameters, we can obtain the homogeneous transformation matrix of M-bot flippers as follows:

\[
\begin{bmatrix}
\cos \theta & -\sin \theta & 0 & 0 \\
\sin \theta & \cos \theta & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
l \\
d
\end{bmatrix}
\]

The four link parameters of M-bot, according to the Denavit–Hartenberg notation, are listed in Table 2.

| Link variable | \( \theta \) | \( \alpha \) | \( l \) | \( D \) |
|---------------|-------------|-------------|-------|-------|
| \( \theta \)   | 0          | 100         | 0     | 0     |

Note. In [10], \( d \) is the distance between the links, \( \theta \) is the angle between the links, \( l \) is the length of the link, and \( \alpha \) is the twist angle between the joint axes.

The position workspace that the flippers of M-bot can move through is drawn as shown in Fig. 9.

The workspace of this arm is a flat disc, where the maximum radius equals the difference between the lengths of the linkages. The result coincides with the design before.

3.2 Dynamic simulation of a tracked robot

3.2.1 Motion simulations using ADAMS software: In order to study its functionality and demonstrate its capability, dynamic simulations of the robotic system were performed. A three-dimensional (3D) mechanical design assembly of the concept that was developed with the help of Solidworks software was exported to ADAMS software. ADAMS [11] is commercial motion simulation software for analysing the behaviour of complex mechanical systems. It allows testing virtual prototypes and optimising designs for performance, without having to build and test physical prototypes.

The process of virtual product development is described in Fig. 9. The 3D model robot is built with Solidworks: it can be either imported to ADAMS directly or used to create a digital mock-up, and then can be imported to the design assembly to make the virtual prototype for functional tests (see Fig. 10).

The specific steps are as follows:

Save the Solidworks model as a para solid type and import it into ADAMS
Edit every component materials properties as steel
Add restraint to every motion component including fix, rotation, belt transport, spring compression, and so on
Set driving motors and edit time function
Run the dynamic simulation.

Fig. 11 is obtained from the screenshot of animation which serves as reference for the optimal design of the robot structure.

3.2.2 Simulation of a jumping mechanism based on MATLAB: A simple programme according to the preceding calculation about the jumping system can reproduce the jumping capability of M-bot. During this process, the jumping kinetic energy of the robot is supplied by elastic potential energy from compressed springs. The initial jumping velocity is calculated and the take-off angle is determined by the arms location, and then the
jumping height and jumping distance can be indicated via the curve relation under a certain take-off angle and initial velocity. There are two take-off angle values given to the robot at different spring compressed length. The concrete parameters have been shown in Table 3 and Figs. 12 and 13.

As can be observed from Fig. 12 and Fig. 13, growing jumping ability is coming with the increase of spring compressed length, of which on the condition of the same 7000 N/s spring constant and 2 kg total weight of robot. Comparatively, the jumping height is higher at a relatively bigger take-off angle, but the jumping distance reduces when take-off angle is bigger. M-bot can tackle both high steps (obstacles height at 0.3 m) or long ditches (obstacles height at 0 m) through these characteristics.

It is worth mentioning that the simulation is impossible to fully reflect the truth without considering the air resistance, energy loss, and the natural working environment.

4 Conclusion

The goal of this project seeks to develop miniature mobile robots that are able to work in a confined environment to search survivors after disasters. The mechanical configuration was designed, which was composed of the drive system, locomotion system, transmission system, and jumping system of the robot.

A complete search and rescue robot must contain control, communication, perception system, and so on, except for the basic mechanical construction. Some complicated dimensions of robots application concerning search and rescue and medical inspection inside the body could not be taken into account in this project, but they are the tool to accomplish the search and rescue mission. The mechanical base is just a mobile carrier to support them. Through remote control, the robot can implement various actions to climb over, avoid or jump over the obstacles, achieving the destinations swiftly. For instance, both the preparation before jumping and the recovery after landing require high control level, while the detection of the environment and survivors and measurement demand a variety of sensors to complete. Gaining the needed information and the instructions demanded by robots are realised through the communication module.

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