

Autonomous Stair Climbing Algorithm for a Small Four-Tracked Robot

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Abstract: In outdoor environments, mobility, adaptability and reliability of a robot are more important than its speed and precise trajectory. From a practical point of view, tracked robots have an advantage over wheeled robots in outdoor applications. The tracked robot is frequently operated by using the remote controller, but the remote operation is not effective for all cases. To overcome some complex obstacles such as rocks or stairs, the information related to the robot posture is required. However, the sensor information is not intuitive to the user to control the robot. In this research, a multi-active crawler robot (MACbot) was developed and the autonomous stair climbing algorithm was implemented to deal with those problems. Various experiments show that the MACbot can climb the stair autonomously.

Keywords: Tracked robot, Autonomous stair climbing, Stability analysis

1. INTRODUCTION

Mobile robotics has received a great deal of attention in the past decades. Mobile robots are being used extensively in industry, military and security environments. One application of a mobile robot is reconnaissance in dangerous areas, including the scene of a fire or a crime. In such situations, tracked robots are usually used and they are operated by the remote control based on the visual information transmitted from a camera mounted on the robot. However, tele-operation is very difficult to control the robot when a robot encounters high stairs or goes into a dark place. Because a common camera cannot provide sufficient information to the operator and the sensor information is not intuitive to the user enough to control the robot, autonomous control is required to overcome an obstacle by itself.

To cope with these problems, various research efforts have been directed toward the development of a robot capable of autonomous stair climbing. To climb the stair well, not only the novel mechanical structures but also the adequate control algorithm are important for the given situations. With the difference in the number of tracks, the arrangement of tracks, structure of a body and so on, the mobility of the tracked robot can be improved [1-3]. For example, a tracked mobile robot based on a linkage mechanism actuator (LMA) developed to conduct autonomous climbing and descending of stairs [4]. This robot is composed of two parallel arms to control the shape of tracks to manage the stability for the stair climbing. On the other hands, the tracked robot can climb the stair autonomously by using vision and a Kalmamn filter in quaternion-based attitude estimation, fusing rotational velocity measurements from a 3-axial gyroscope, and measurements of the stair edges [5]. Besides, there are many research related with the autonomous stair climbing [6].

This paper presents the multi-active crawler robot

(MACbot) with the ability of autonomous stair climbing. The MACbot has four track modules that can be rotated freely about their pivots located at the center of track to passively adapt the terrain and independently activated to travel on a fine terrain. Otherwise, on the rough terrain, the clutch mechanism enables each track to rotate actively around its pivot to climb over obstacles. With four motors located at each track, it can operate by running four tracks simultaneously and crawling tracks as necessary.

To climb the stair autonomously, some sensors feed the posture information of the robot back to the controller. The autonomous stair climbing algorithm is based on the kinematics and static analysis during stair climbing and it is implemented to the MACbot. Various experiments show that the MACbot can climb the stair autonomously.

2. MULTI-ACTIVE CRAWLER ROBOT

2.1 Concept of MACbot

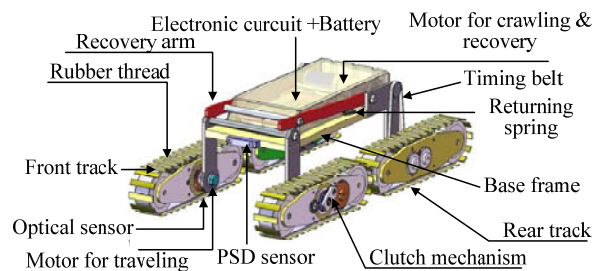


Fig. 1 Schematic of MACbot

The MACbot was designed for outdoor environment applications so that its design was focused on power, adaptability and reliability in operation. As shown in Fig. 1, the MACbot is composed of four track modules. The front track module has a clutch mechanism based on a planetary gear train and it provides two driving modes; one is the normal mode (Fig. 2(I)) for regular terrain and the other is the obstacle mode for rough

terrain (Fig. 2(II-IV)). The switching motion between the two modes depends on the rotational direction of the motor installed at each track.

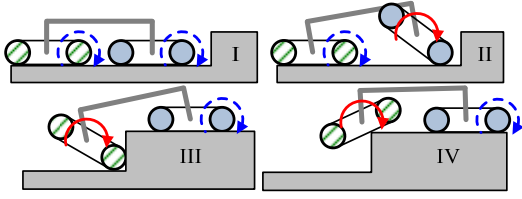


Fig. 2 Climbing operation.

When a higher step appears as shown in Fig. 2, the MACbot cannot go over the steps using the normal mode. In this case, the obstacle mode is activated. First, the two front tracks reach the obstacle (I) and start to rotate to climb it (II). After the two front tracks successfully stand on the obstacle (III), the two rear tracks approach the steps and also climb over the obstacle (IV).

2.2 Prototype of MACbot

The MACbot capable of overcoming high obstacles was fabricated, as shown in Fig. 3 and its specifications were listed in Table 1. The robot uses five DC motors including speed reducers and encoders. Two microcontroller processor units (ATMega 128) with small motor driver ICs were used to control motors. To measure the distance between the robot and the obstacle, one PSD sensor (GP2D120XJ00F) is mounted at the front of the robot. Three optical sensors are used to provide the rotation angle of four tracks around their pivots. The 3-axis accelerometer (A7260 K638051) is also integrated to measure the inclination angle of the body and the direction of gravity. Various experiments were conducted to evaluate the performance of the robot's mobility including autonomous stair climbing.

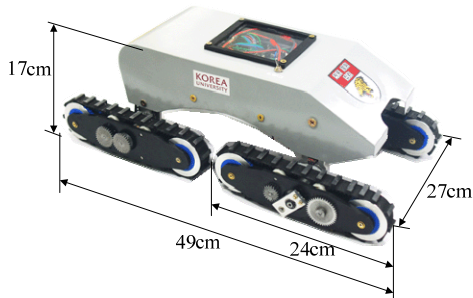


Fig. 3 Prototype of MACbot.

Table 1. Specifications of MACbot.

Parameters	MACbot
Total weight	4.1kg
Maximum height of obstacle	18 cm
Speed in normal mode	20 cm/s
Speed in obstacle mode	8 cm/s
Ability in stair climbing	15cm in height 30cm in depth

3. STABILITY ANALYSIS

When the MACbot encounters the stairs, it changes the operation mode from the normal to the obstacle mode, as explained in Section 2.1. During this motion, the contact configuration between the tracks and the ground changes and sometimes the robot can be overturned. Therefore, a safe working area must be considered for all changes in the climbing motion. The center of mass (CM) of the MACbot is constantly changing and the position of CM depends on both the track angles (α and β) and the body angle (γ). By using the feedback information from the tilt sensor, all states of the robot can be described in real time. To conduct stable stair climbing, two criteria are required: one for the stability of CM and the other for the moment balance during stair climbing.

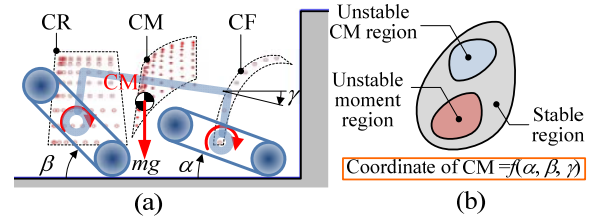


Fig. 4 Stability criteria: (a) possible locations of CF, CM and CR, and (b) diagram for stable region.

Assume that the MACbot is on the stair with two contact points. If the point of the mass center projected to the ground is out of the stable region, as shown in Fig. 5(a), the robot will be overturned. Although the mass center is placed in the stable region, as shown in Fig. 5(b), the robot may be overturned when it tries to rotate the rear tracks to ride on the upper step. To prevent the unbalance problem of the robot during the whole climbing process, the locations of the mass center must be investigated. The methods to solve these problems will be explained in more detail.

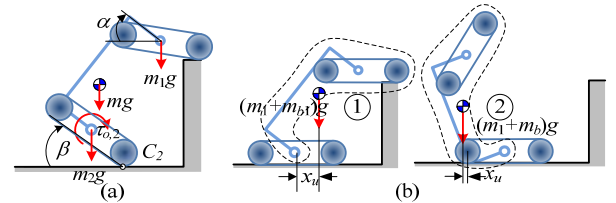


Fig. 5 Moment unbalances during stair climbing.

3.1 Stability of Mass Center

The robot configuration related to the geometry of the stair is continuously calculated throughout the climbing process until the robot completes the climbing operation. For stability analysis, three types of information such as the rotating angles of tracks, the distance from the robot to the rising step edge, and the inclination angle of the body are used, as shown in Fig. 6(a). Let the rotation angles of the front track (α) and rear track (β) vary. With this information, the configuration of the robot can be established and the

center of mass can be obtained as follows:

$$\begin{aligned} x_{cm} &= x_{O,2} + d_{cm} \cos \gamma - h_{cm} \sin \gamma \\ y_{cm} &= y_{O,2} + d_{cm} \sin \gamma + h_{cm} \cos \gamma \end{aligned} \quad (1)$$

where $x_{O,2}$ and $y_{O,2}$ are the mass center of the two rear tracks, d_{cm} and h_{cm} are the distance to and height of the mass center of the robot, respectively. To maintain the stable motion, x_{cm} must be placed between the contact position of the front track (x_{C1}) and the rear track (x_{C2}). All points that satisfy this condition are stable.

In the next state (Fig. 6(b)), the robot starts to ride on the stair edge. With the same approach stated above, the position of the mass center can be determined and the height of obstacle can be estimated by

$$h_o = \left(\frac{y_{O,1} + r \cos \alpha - \left(\frac{l_t + 2r}{2} \right) \sin \alpha}{1 - \sin \alpha} \right) \quad (2)$$

where $y_{O,1}$ is the mass center of the front tracks in the y direction, r is the radius of the track and l_t is the length of the track. After the front track stands on the upper step, the rear track approaches and rides on the step edge to complete the climb process at the first step.

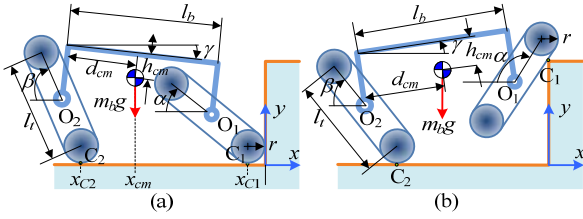


Fig. 6 Schematic for geometry calculation for stair climbing.

The center of mass can be fully managed, and it is in either the stable region, unstable region or marginal region. By conducting all geometry calculations for full stair climbing process, all locations of the mass center of the robot are obtained, as shown in Fig. 7. The operation of the robot must stop at the margin. When the obstacle height decreases, the unstable and marginal regions decrease as well. According to the analysis, the unstable region starts disappearing when the obstacle height is 0.13m, which means that no danger of unstable motion exists for the robot operation.

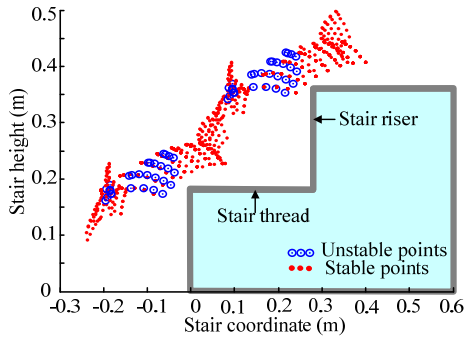


Fig. 7 Locations of mass center of MACbot.

3.2. Moment Balance

After the front track of the MACbot is placed on the upper step, the motor installed at the rear track applies the torque $\tau_{O,2}$ to rotate the rear track. Then the reactive torque is exerted on the body at point O_2 , as shown in Fig. 8. As the obstacle height increases, the torque $\tau_{\text{anti-rollover}}$ contributed by the weight of the body and front track decreases. Because the distance between the mass center of the body and the point O_2 gets shorter, the robot is more likely to roll over. The torques $\tau_{\text{anti-rollover}}$ and $\tau_{O,2}$ can be given by

$$\tau_{\text{anti-rollover}} = (m_1 + m_{b1}) g l_b \cos \gamma \quad (3)$$

$$\tau_{O,2} = (m_2 + m_{b2}) g l_t / 2 \quad (4)$$

where m_1 and m_2 are the mass of the front and rear tracks, and m_{b1} and m_{b2} are the distributed mass of the robot body at the front and rear tracks, respectively.

To prevent the rollover of the body, $\tau_{\text{anti-rollover}}$ must be larger than $\tau_{O,2}$. When the inclination angle of the body increases from zero to 90° , the behavior of $\tau_{\text{anti-rollover}}$ and $\tau_{O,2}$ varies, as shown in Fig. 9. If the inclination angle of the body is smaller than a critical value of γ_C or the obstacle height is smaller than a certain value h_{limit} , the robot can avoid rollover. The maximum value of h_{limit} is 13cm and it can be obtained by

$$h_{\text{limit}} = l_b \sin \gamma_C \quad (5)$$

where l_b is 21cm and γ_C is 43° . From the analysis explained above, the obstacle can be classified into two cases: *low obstacle* whose height is lower than 13 cm and *high obstacle* higher than 13 cm. The rollover problem never occurs for low obstacles.

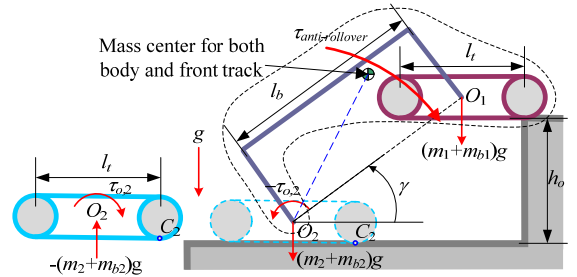


Fig. 8 Free body diagram for MACbot

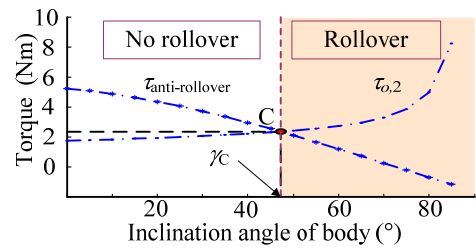


Fig. 9 Moment condition for anti-rollover.

4. AUTONOMOUS STAIR CLIMBING

The MACbot can climb the stairs autonomously by executing a proposed scheme based on the current information provided by the sensors. Furthermore, the stability analysis is incorporated into the autonomous stair climbing algorithm to guarantee the stable motion of the robot at the same time. It is very important to know the geometry information of the stair which directly affects successful stair climbing. In other words, the robot should estimate the size of the stair to decide how to climb it.

Figure 10 shows the sequence of robot motions. At the beginning, the robot moves closely to the stair. The PSD sensor continuously provides the distance from the robot to the stair. When the distance to the step riser becomes smaller than 60 cm, the rear tracks rotate 110° to avoid the unbalance moment condition, as shown in Fig. 10(a). At the next step, when the distance is smaller than a half of the track length, the front tracks rotate 200° to ride on the upper step, as shown in Fig. 10(b). At 90° of the angle of the front track, the step depth d_s can be obtained as the difference between d measured by the PSD sensor and the track radius r .

Moreover, once the front tracks fully stand on the upper step, the step height can be estimated by (2). After locating on the upper step, the robot moves in a distance of $d_{x(2,3)}$, which is the translated distance in the x direction from step 2 to step 3, before the rear tracks start rotating to ride on the upper step, as shown in Fig. 10(c) and (d). The inclination angle of the robot body γ_3 should be smaller than 43° to avoid rollover. Furthermore, the rotation angle of the front track and rear track must be controlled to guarantee that the distance between the two contact points C_1 and C_2 is shorter than the stair depth d_s . From this moment, as shown in Fig. 10(e), the rear and front tracks simultaneously rotate until the front tracks fully ride on the upper step. To get the desired posture as shown in Fig. 10(f), the required rotation angles of the front and rear tracks are determined, as shown in Table 2. The control value means the angles to rotate the front and rear tracks and $\alpha_{i,d}$, $\beta_{i,d}$, and $\gamma_{i,d}$ are the desired values for the i -th state

to climb the stairs. The rotation angle of the rear track at the end of step 3 and step 4 can be obtained by

$$\beta_3 = \arccos \left[\frac{2}{l_t} \left(\frac{l_t}{2} \cos \alpha_3 + l_b \cos \gamma_3 - d_s \right) \right] \quad (6)$$

$$\beta_4 = \arcsin \left[\frac{2}{l_t} \left(h_o - l_b \sin \gamma_4 + \frac{l_t}{2} \sin \alpha_4 \right) \right] \quad (7)$$

By using this strategy, the inclination of the body can be maintained at a small value. After this step, a new sequence of operations is repeated from step 2, as described in Fig. 10(b). All operations will be halted if the stability condition is conflicted.

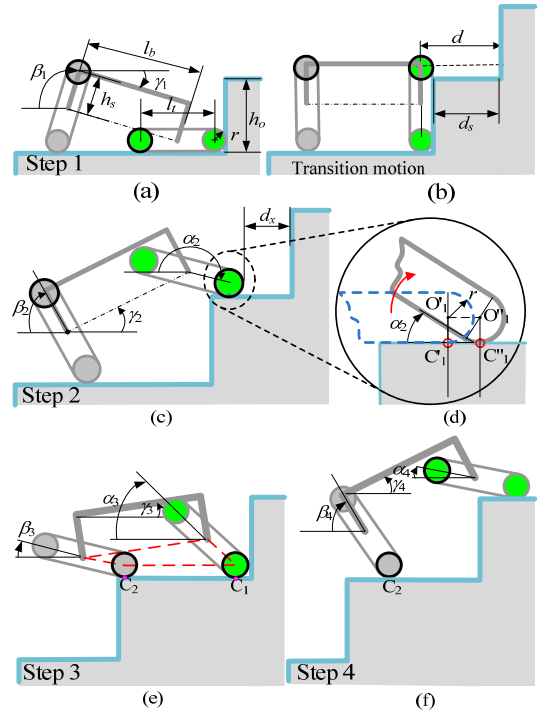


Fig. 10 Sequence of autonomous stair climbing motion.

Table 2. Control values required to climb stairs at each steps.

State	Rotation angle	Desired value	Control value	Rotation angle	Desired value	Control value	Inclination angle	Desired value	Measured value
Initial state	α_0	0°	0°	β_0	0°	0°	γ_0	-	0°
Step 1	α_1	0°	0°	β_1	110°	$\beta_{1,d} - \beta_0$	γ_1	-	γ_1
Step 2	α_2	200°	$\alpha_{2,d} - \alpha_1$	β_2	$\beta_1 - \gamma_1 - \gamma_2$	0°	γ_2	-	γ_1
Translated distance : $d_{x(2,3)} = d_s - (l_t - h_o + r\alpha_2 + 2r)$									
Step 3	α_3	$\alpha_2 + \gamma_2 - \gamma_{3,d}$	0°	β_3	Eq. (6)	$\beta_{3,d} - \beta_2 + \pi$	γ_3	35°	-
Step 4	α_4	20°	$\alpha_{4,d} - \alpha_3 + \pi$	β_4	Eq. (7)	$\beta_{4,d} - \beta_3$	γ_4	35°	-

5. EXPERIMENTS

In order to verify the performance of the stair climbing algorithm of the MACbot, various experiments were conducted for autonomous stair climbing. The algorithm is based on the stability condition that is computed at a certain time and the normal-sized stair was used as shown in Fig. 11.

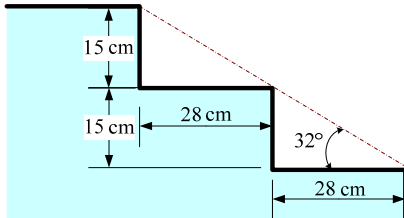


Fig. 11 Shape of stairs.

Figure 12 shows the sequence of autonomous stair climbing. To climb the stairs, the MACbot first measures the distance to the stair by using a PSD sensor. If the distance is smaller than 60 cm, then the rear tracks rotate 110° (i.e., (a)). Until the distance is the same with a half of the track length, the robot continuously approaches the obstacle. At the moment when the distance is smaller than a half of the track length, the front tracks rotate 200° to ride on the first step (i.e., (b)). Since the step height and width were estimated as presented in section 3.1 and section 4, the front tracks move to contact the rising side of the next step with the distance of $d_{r(2,3)}$, as shown in Table 2. Based on the calculation, the robot moves a few seconds. The rear tracks then rotate to lift the robot body to the upper step (i.e., (g)). The front tracks rotate to ride on the next step and the sequence of these actions are repeated until the robot reaches the end of the stair. Both information on the distance to the obstacle and the inclination angle of the body is used to decide whether the stair is ended or not. If the inclination angle is lower than 5° and the distance is greater than 50 cm, autonomous stair climbing is completed (i.e., (h)). The experimental results demonstrate that the MACbot can climb stairs reasonably well.

6. CONCLUSIONS

In this research, the autonomous stair climbing algorithm is developed and successfully implemented to the MACbot. The stability algorithm of stair climbing always ensures that the center of gravity of the MACbot can be placed in the stable region. The autonomous stair climbing algorithm is used to guide the MACbot to know how to change its configuration to overcome the stair and to avoid the unstable areas. This algorithm greatly improves the controllability of the MACbot, while the burden of the operator is decreased.

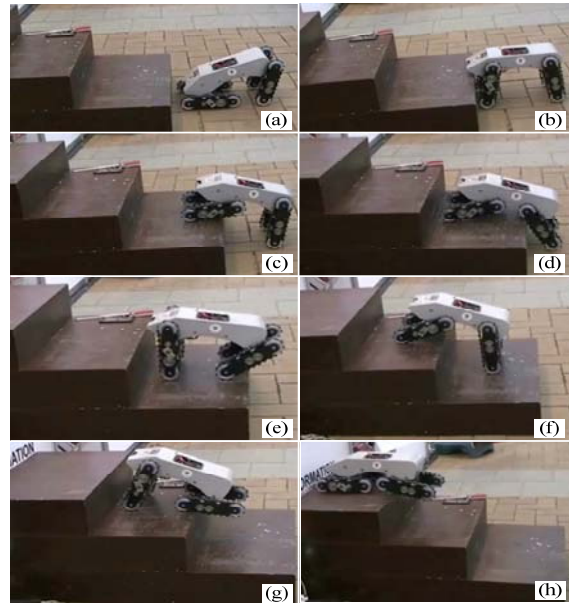


Fig. 12 Autonomous stair climbing.

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