A New Mechatronic Component for Adjusting the Footprint of Tracked Rescue Robots

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Abstract. There is no ideal footprint for a rescue robot. In some situations, for example when climbing up a rubble pile or stairs, the footprint has to be large to maximize traction and to prevent tilting over. In other situations, for example when negotiating narrow passages or doorways, the footprint has to be small to prevent to get stuck. The common approach is to use flippers, i.e., additional support tracks that can change their posture relative to the main locomotion tracks. Here a novel mechatronic design for flippers is presented that overcomes a significant drawback in the state of the art approaches, namely the large forces in the joint between main locomotion tracks and flippers. Instead of directly driving this joint to change the posture, a link mechanism driven by a ballscrew is used. In this paper, a formal analysis of the new mechanism is presented including a comparison to the state of the art. Furthermore, a concrete implementation and results from practical experiments that support the formal analysis are presented.

1 Introduction

Moving around in an unstructured environment is the principal ability a mobile robot must have to be a rescue robot. Locomotion systems in general can be classified as wheeled, tracked or legged. In the RoboCup Rescue 2005 competition tracked robots were very popular and successful. Figure 1 shows an overview of the different tracked robots in this league in 2005. This type of locomotion is often considered as the most versatile locomotion system as it can handle relatively large obstacles and loose soil [Har97][Won01]. Some versions of tracked vehicles are even used by several teams, namely the Tarantula and RobHaz DT-3. The Tarantula is a typical toy car substantiating the concept that low cost platform can be deployed for rescue application. The Tarantula is R/C vehicle with four tracked articulated arms which can climb over obstacles, steps or stairs. The team Freiburg for example very successfully used this toy [KSD+06]. The RobHaz DT-3 is a sturdy commercial platform. It is based on a passive double track platform. There were three teams using this platform in the competition with impressive performances, namely ROBHAZ-DT3 [LKLP06], CASualty [KKP+06], and the Intelligent Robot Laboratory team [TT06].

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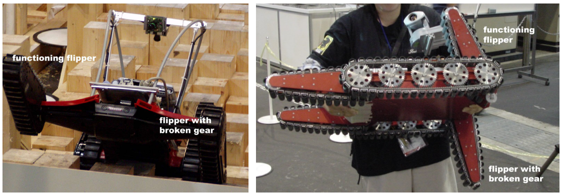
Fig. 1. Flippers as additional tracks that can change their posture relative to the main locomotion tracks are a very common approach to allow for a flexible footprint. The general advantages of this locomotion principle is for example indicated by the many teams that chose this approach for their robots. Some examples from RoboCup 2005 are shown above.

Though a differential drive based on two tracks is simple and in principle already very capable, there is a significant problem especially for rescue robots. A critical aspect is that it is almost impossible to select the right parameters for a single pair of tracks. For some situations, for example when negotiating narrow passages, the footprint of the robot and hence the length of the tracks should be small. When climbing large obstacles, slopes or stairs the footprint should be large. The common solution to this problem is to use additional tracks that can change their posture relative to the main robot body. Note that all robots in figure 1 are equipped with according flippers. The state of the art for changing the posture of the flipper is to directly drive the joint between the additional small track and the main locomotion system. This approach has the tremendous disadvantage that due to the large forces on this active joint it is extremely difficult to construct mechanisms that are sufficiently stable and still within feasible size and weight limits. Broken joints are hence a common phenomena (figure 2). Here a novel design from the IUB rescue robot team [BC06] is presented that circumvents these problems.

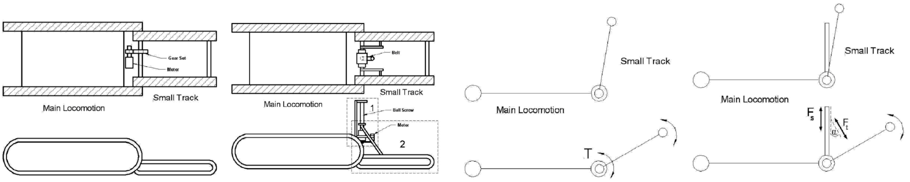
2 The Underlying Concept

The standard approach to change the posture of a flipper is to directly drive the joint as shown in figure 3. This can be done by spur or worm gear or a belt or chain drive. But no matter what mechanism is used, it has to take quite some stress. First of all, it has to provide high forces for moving the flipper under load, especially for pushing it down when the full weight of the robot is supported by it. Second, it is subject to shocks and impacts, for example when the robot drives over bumps, stairs, etc. Especially these forces can be very high and they are very hard to predict. It is hence almost impossible to design a fail-safe mechanism



(a) (b)

Fig. 2. Large forces have to be provided when using the standard approach to directly drive the joint of a flipper. In addition, shocks to the tracks are likely to occur in rough locomotion conditions. These can cause large load changes and huge unpredictable dynamic forces directly at the transmission in the joint. Broken transmissions in the flipper-joints are hence a common problem, not only for simple bases like the Tarantula (a) but even for advanced robots like the winner of the RoboCup 2005 rescue competition (b).



(a) (b) (c) (d)

Fig. 3. A sketch of a classical locomotion system with flipper (a) and its basic free body diagram (c) compared to a sketch (b) and the basic free body diagram (d) of the novel system.

within feasible weight and size limits with this approach. Accordingly, broken flipper joints are a common problem (figure 2).

The novel flipper design presented here consists of a ball screw, a passive link and a motor (figure 3). As shown in the formal analysis later on, the driving force that needs to be provided by the motor is smaller with this set-up. Furthermore, all shocks go against the passive link and the ball screw, which in contrast to spur/worm-gears or belt/chain-drives can be easily laid out to absorb them without any damage. Figure 4 also shows an implementation of the flipper itself.

3 Formal Analysis of the Design

When the robot moves around on the floor, the small track is up to minimize the footprint. Whenever the robot has to move over a big obstacle or up, respectively down a stair, the small track is pushed down to the same level of the big track. The small track is moved up from or down to the floor by a ball screw. The crucial parameters for the ball screw are the thrust force and the stroke of movement. The thrust force of the ball screw determines the force for pulling the small

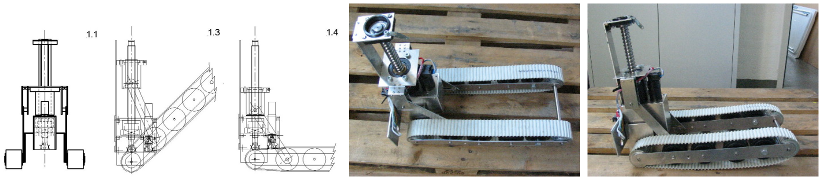


Fig. 4. An implementation of the novel flipper design

track up, respectively pushing the small track down. First, the thrust force is determined that is needed to push the small track down. After that we will find the second parameter, the stroke of movement. First we consider the situation that robot is on a two points support with an angle θ with respect to the floor. To calculate the thrust force of the ball screw, the force in the direction of $\cos\theta$ has to be considered. The maximum value of $\cos\theta$ is one when θ is zero. The maximum thrust force is hence needed in a situation when θ is zero.

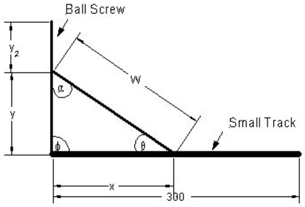
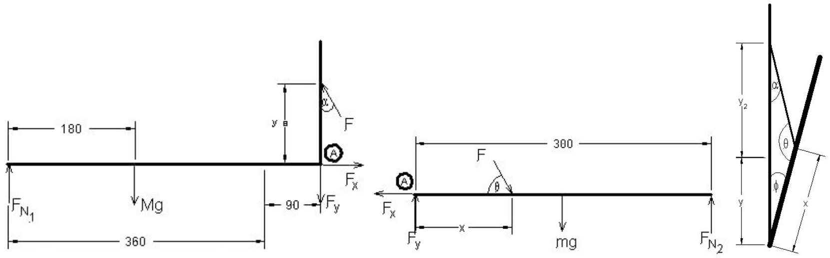


Fig. 5. The core parameters in the free body diagram of the ball screw and the small track

In the following, the maximum thrust force is analyzed following the free body diagrams in figures 5 and 6. First of all, it is assumed that the ball screw is fixed to the robot such that it forms with the robot body and its main locomotion track a single object as shown in figure 6(a). The small track of the flipper is a second object as shown in figure 6(b). As the main locomotion track of Rugbot is 650mm long, a length of 300 mm is chosen for the small track. With this set up, Rugbot is always supported on stairs when the flipper is on the ground. From the stability viewpoint, the stairs can be considered in the worst case like an obstacle on the ground with just two support points at the extrema of the footprint. F and y_2 are most important as they determine the selection of the ball screw and the motor. Also, the length L of the mechanism, i.e., y plus y_2, is of interest. Given the height of a Rugbot that is 550 mm, the mechanism should not extend over it. So, y is the minimum height of the ball screw to which we want to lower down the small track on to the floor. And y_2 is the stroke of the ball screw to move the small track up from the floor. Therefore, $\mathrm{F}\cos\alpha$ is a lower constraint on the thrust force. The common condition of the free body diagrams of figure 6(a) and 6(b) is that the robot is stable without any movement in any



(a) (b) (c)

Fig. 6. More detailed free body diagrams and parameters of (a) the main track system with the ball screw and (b) the small track. The free body diagram of the ball screw and the small track when the flipper is moved up (c).

direction. So, the total force in x direction and y direction must be zero. Hence, we get

$$\mathrm{Mg} + \mathrm{F}_y - \mathrm{F}\cos(\alpha) = \mathrm{F}_{N_1} \tag{1}$$

$$\mathrm{F}\sin(\alpha) = \mathrm{F}_x \tag{2}$$

$$\mathrm{mg} - \mathrm{F}_y + \mathrm{F}\sin(\theta) = \mathrm{F}_{N_2} \tag{3}$$

$$\mathrm{F}\cos(\theta) = \mathrm{F}_x \tag{4}$$

$$\mathrm{y} = \mathrm{x}\tan(\theta) \tag{5}$$

$$\theta + \alpha = 90\,\mathrm{deg} \tag{6}$$

Rearrange (1) and (3) with (6)

$$\mathrm{F}_{N_1} + \mathrm{F}_{N_2} = \mathrm{Mg} + \mathrm{mg} + \mathrm{F}(\sin(\theta) - \cos(\alpha)) \tag{7}$$

$$\mathrm{F}_{N_1} + \mathrm{F}_{N_2} = \mathrm{Mg} + \mathrm{mg} \tag{8}$$

The sum of moment about A:

$$\mathrm{Mg} \times 270 + \mathrm{F}\sin(\alpha)\mathrm{y} = \mathrm{F}_{N_1} \times 450 \tag{9}$$

$$\mathrm{F}_{N_1} = \frac{\mathrm{Mg} \times 270 + \mathrm{F}\sin(\alpha)\mathrm{y}}{450} \tag{10}$$

$$\mathrm{mg} \times 150 + \mathrm{F}\sin(\theta)\mathrm{x} = \mathrm{F}_{N_2} \times 300 \tag{11}$$

$$\mathrm{F}_{N_2} = \frac{\mathrm{mg} \times 150 + \mathrm{F}\sin(\theta)\mathrm{x}}{300} \tag{12}$$

From (5), (6), (7) and (8)

$$\mathrm{Mg} + \mathrm{mg} = \frac{\mathrm{Mg} \times 270 + \mathrm{F}\sin(\alpha)\mathrm{y}}{450} + \frac{\mathrm{mg} \times 150 + \mathrm{F}\sin(\theta)\mathrm{x}}{300} \tag{13}$$

$$0.4 \times \mathrm{Mg} + 0.5 \times \mathrm{mg} = \mathrm{F} \times \left(\frac{\sin(\alpha)\mathrm{x}\tan(\theta)}{450} + \frac{\sin(\theta)\mathrm{x}}{300}\right) \tag{14}$$

$$\mathrm{F} = \frac{225}{\frac{\sin(\alpha)\mathrm{x}\tan(\theta)}{450} + \frac{\sin(\theta)\mathrm{x}}{300}} \tag{15}$$

With equation (15), we have the relation between thrust force $F\cos(\alpha)$, the point of push/pull force connect to small track x, and the initial length of the ball screw y. With a numerical analysis, different variations of these parameters can be computed. Based on the size aspect of Rugbot, the size L of the mechanism is the first parameter that should be specified.

Then, the values of x and y are used to calculate the stroke y_2 by the next free body diagram shown in figure 6(c). Given a minimum angle of 10 degrees between the small track and the ball screw, we get the relation between x, y, and y_2 as:

$$\mathrm{W} = \frac{\mathrm{x}}{\cos(\theta)} \tag{16}$$

$$\alpha = \arcsin(\frac{\mathrm{x} \times \sin(10)}{\mathrm{W}}) \tag{17}$$

$$\mathrm{y}_2 = \frac{\mathrm{W} \times \sin(170 - \alpha)}{\sin(10)} - \mathrm{y} \tag{18}$$

With the height limit of the robot, we can analyze the set of the data including thrust force, x, θ, y, and y_2. As we specified in the beginning that the first priority in optimization is L, so we analyze the data set with L equal 400 mm, 450 mm, 500 mm, and 550 mm by using the present parameters of the Given the basic parameters of Rugbot with M = 50 kg, m = 5 kg, and g = 10 m/s^2, a numerical analysis can be done with L equals 400 mm, 450 mm, 500 mm, and 550 mm (table 1).

Table 1. Results of the numerical analysis of the parameters for different mechanism lengths L

L: mm	**θ: deg**	**F: N**	**x: mm**	**y: mm**	**y_2: mm**
400	50	334.7	158	188.3	211.7
450	52	297.1	173	221.5	228.5
500	52	267.7	192	253.6	253.6
550	51	243.6	214	284.7	284.7

It can be seen that there is an inverse relation between the thrust force and the upper limit. If the upper limit is increased by about 15 cm, there is almost half the thrust force needed than with the shorter upper limit. Based on the parameters of Rugbot and on available ball screws, in the final implementation a ball screw with l=500 mm was chosen leading to a thrust force as 267.7 N.

The benefits of this design concept can also be illustrated by considering the case when the robot faces a ramp as shown in figure 7. Before the robot is going up the ramp, the component has lifted the small track up. When Rugbot is going up the ramp, an inclinometer senses the angle of the ramp φ and the component starts to lay down the track simultaneously. For tele-operated robots this is of course done by the operator. Suppose the robot is moving over the ramp with an approximately constant speed and the same holds for the angle ϕ. So, ϕ is varied

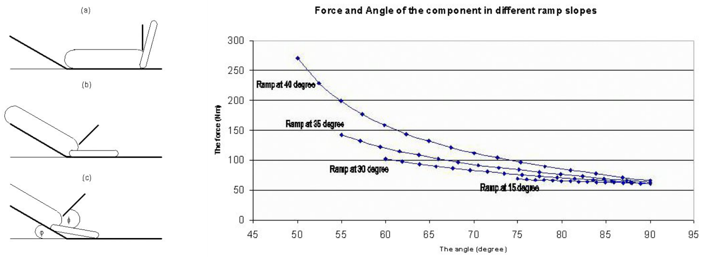


Fig. 7. The new flipper design facing a ramp (left). The forces in dependence of the posture angle for different ramp angles (right).

in each step the robot is moving up the ramp, which can be determined based on φ, robot speed, and the parameters of the flipper. Moreover, the force used to lay down the small track against the floor also can be analyzed to verify the strength of the motor and the ball screw. Figure 7 shows the graphs for several ramp angles with one second period between each data point and a robot speed of 20 mm/sec. As the robot moves up the ramp, the value of ϕ is increasing while the force is decreasing. The analysis also shows that φ not only effects the value of ϕ, but also the force. Larger angles φ need higher forces to put the small track against the floor at the beginning steps to move over the ramp. Note that the overall forces are by far within the allowable range of the ball screw and can be easily provided by the chosen motor.

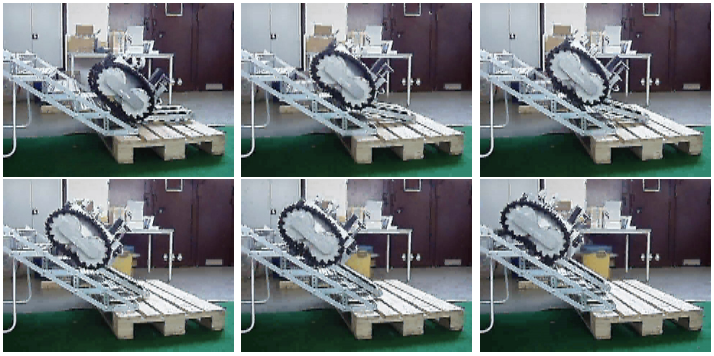


Fig. 8. Rugbot going up stairs

The formal analysis is also supported by all field tests of the robots. The flippers are very sturdy. The can even be used as a handle to pull or lift the whole weight of the robot without the slightest disturbance to the joint between the robot and its flipper. In addition, they support the climbing of obstacles and stairs exactly as they are supposed to do (figure 8).

4 Conclusion

Adjustable support tracks are a common concept for changing the footprint of a robot. Here, a novel mechanism for flipper design was presented that overcomes the flaws of the standard approach to directly drive the joint between the robot body with the main locomotion tracks and the flipper. Instead, a ballscrew and a passive link are used.

References

[BC06] Birk, A., Carpin, S.: Rescue robotics - a crucial milestone on the road to autonomous systems. Advanced Robotics Journal 20(5) (2006)

[Har97] Hardarsson, F.: Locomotion for difficult terrain. Technical report, Mechatronics Lab, Dept. of Machine Design (1997)

[KKP$^+$06] Kadous, M.W., Kodagoda, S., Paxman, J., Ryan, M., Sammut, C., Sheh, R., Miro, J.V., Zaitseff, J.: Robocuprescue - robot league team CASualty (australia). In: Bredenfeld, A., Jacoff, A., Noda, I., Takahashi, Y. (eds.) RoboCup 2005. LNCS (LNAI), vol. 4020, Springer, Heidelberg (2006)

[KSD$^+$06] Kleiner, A., Steder, B., Dornhege, C., Meyer-Delius, D., Prediger, J., Stueckler, J., Glogowski, K., Thurner, M., Luber, M., Schnell, M., Kuemmerle, R., Burk, T., Bräuer, T., Nebel, B.: Robocuprescue - robot league team rescuerobots freiburg (germany). In: Bredenfeld, A., Jacoff, A., Noda, I., Takahashi, Y. (eds.) RoboCup 2005. LNCS (LNAI), vol. 4020, Springer, Heidelberg (2006)

[LKLP06] Lee, W., Kang, S., Lee, S., Park, C.: Robocuprescue - robot league team ROBHAZ-DT3 (south korea). In: Noda, I., Jacoff, A., Bredenfeld, A., Takahashi, Y. (eds.) RoboCup 2005. LNCS (LNAI), vol. 4020, Springer, Heidelberg (2006)

[TT06] Tsubouchi, T., Tanaka, A.: Robocuprescue - robot league team Intelligent Robot Laboratory (japan). In: Noda, I., Jacoff, A., Bredenfeld, A., Takahashi, Y. (eds.) RoboCup 2005: Robot Soccer World Cup IX. Lecture Notes in Artificial Intelligence (LNAI), vol. 4020, Springer, Heidelberg (2006)

[Won01] Wong, J.Y.: Theory of Ground Vehicle.ition, 3rd edn. ch. 4.5, John Wiley and Sons, Chichester (2001)