Using Rescue Robots to Increase Construction Site Safety

Winai Chonnaparamutt
School of Engineering and Science
International University Bremen
Campus Ring 1
28759 Bremen, Germany
Tel: +49 (0) 421 200 3185, Fax: +49 (0) 421 200 3103
e-mail: w.chonnaparamutt@iu-bremen.de

Prof. Dr. Andreas Birk
School of Engineering and Science
International University Bremen
Campus Ring 1
28759 Bremen, Germany
Tel: +49 (0) 421 200 3113, Fax: +49 (0) 421 200 3103
e-mail: a.birk@iu-bremen.de

Abstract: Robotics technology is continuously gaining in importance in many applications. Especially mobile robots are already widely used in many fields including construction sites. Accidents in the construction industry have been identified as one of the most hazardous incidents compared to other work environments. We therefore propose to consider robotics technology to improve this situation. This paper introduces the idea of applying rescue robots as an accident prevention and first aid provision system at construction sites. In doing so, the mobility of the robot is a key issue. The paper presents a special robot, the rugbot, and a novel mechatronic component, a so-called flipper, which can be used to adapt the footprint of the robot. This allows the robot to negotiate a difficult environment as it can be found at construction sites.

Keywords: Mechatronics, Tracked Locomotion, Rescue Robots, Construction Site Safety.

1. INTRODUCTION

Accidents in the construction industry have been identified as most hazardous incidents compared to other work environments. Worldwide, construction workers are three times more likely to be killed and twice as likely to be injured as workers in other occupations [3]. The types of accidents are diverse, ranging from minor injure for individual workers, e.g. slips or falls, to a major accidents, like site collapsing or a break out of fire [21][5]. There is significant research to find out the causes of accidents during construction work. Chia-Fen Chi et al. [2] discuss for example prevention measures for fall accidents in the construction industry based on statistical analysis of 621 cases in Taiwan. The main factors affecting the safety performance in the Chinese construction industry were e.g. analyzed by C.M. Tam et al. [19]. Not only the causes of the accident, but also the pre-accident and post-accident tasks have been investigated [20][12]. Although robotics technology has been implemented in the construction industry in the aspect of the construction work recently, little information is available on safety related work from the robotics perspective. Ger Mass et al. [13] showed examples of the influence of automation and robotics on the performance of construction. One example is the construction engineering with a contribution about the improvement of Human Machine Technologies, and about worker safety on the building site. Nevertheless, no work has been done on the utilizing of robotics technology for accidents in the construction industry.

Robotics technology is continuously gaining in importance in many applications. Especially mobile robots are already widely used for surveillance, inspection and transportation tasks. After the Hyogoken-Nambu Earthquake happened in Kansai area in Japan in 1995, which is known as the great Hanshin - Awaji Earthquake, a new challenging field has been proposed: Rescue Robotics [18]. Satoshi Tadokoro et al. [17] noted the tasks for the ideal rescue robotics equipment, such as: searching for human bodies; excavation of the debris; handling human bodies etc. Fire fighting robots also have been of topic of research. They are studied in academia but they are also used in several application areas [15][1][9][8][7][6]. For example, Nobuo Kimura [10] describe the conceptual design and test results of the advanced robot for fire fighting and disaster prevention. The robot helps disaster-fighting personnel to grasp disaster status, to extinguish fires and to prevent the disaster spreading in a high temperature and smoke environment at a petroleum production facility. Akira Kobayashi et al. [11] also work in this area. They propose the specification of the rescue robots functions in fire hazard incidents. The robots should be systematically characterized as follows: operating at emergency only, realizing of broad area service based on quick mobility, and collecting and transmitting of the high quality information of disaster prevention by the high performance sensing function. Kazuyoshi Miyazawa [14] also presented the development of the latest high-technology robots from the Tokyo Fire Department that can cope with major urban disasters.

2. KEY ASPECTS FOR USING RESCUE ROBOTS FOR CONSTRUCTION SITE SAFETY

Although the research on rescue and fire fighting robots is mainly based on scenarios from catastrophes such as earthquakes or major fires, certain functions are as well applicable to the safety development on the construction industry. Naoji Shiroma et al. [16] noticed the potential daily usage for the rescue robot in form of patrol and guide tasks or for general data collection. Here we propose to also consider the benefits of rescue robots for construction site safety. The robot can be utilized as an accident prevention and first aid provision system for dangerous working areas, especially construction sites. For instance, the robot can be designed to localize and detect the risks on the site that cannot be prevented, to inform construction workers with warning signals of approaching danger, and to prevent people falling into openings in floors [13]. The example of preventing a fire incident [5] is to integrate a LPG sensor to the robot for sensing any suspicion of LPG. And a manipulator mobile robot also can prevent the incident by keeping the site clean from rubbish in every evening of the day. The missions of the robot are to diminish the accident and to rescue the site in case the prevention is failed. Each task needs different basic features for the robot.

- Accident prevention requires
  - a fast locomotion platform to patrol the ground floor of the site,
  - an LPG sensor and a smoke sensor to sense a cause of a fire,
  - a manipulator and a rubbish bin to collect the small rubbish from the site.

- Site rescue requires
  - a sturdy locomotion platform to overcome the unstructured environment of the site,
  - a camera to transfer the vision data of the site to the operator station,
  - a fire extinguisher to stop a fire.

The main feature that must have in every rescue robot is the locomotion component. Wheeled locomotion has the advantages of smoothness and speed in relatively even terrain, on the other hand, this locomotion type generally has trouble if an obstacle is higher than the radius of the wheels or if the ground has steps, holes or ditches. For tracked locomotion, this is often considered as the most versatile locomotion system and can handle relatively large obstacles and loose soil, and has an ability to handle large hinders and small holes and ditches, as well as good payload capacity. This type of locomotion is the most suitable to surmount obstacles, negotiate stairways, and is able to adapt to terrain variations [4][22]. Wheeled locomotion may suit the accident prevention task, while the site rescue is better to use the tracked locomotion. Nevertheless, the environment of the construction site is considered as an unstructured area, which might be more safety to use the tracked locomotion for both missions.

Figure 1: Rugbot with the novel flipper at RoboCup 2005 in Osaka, Japan

Figure 2: The novel flipper

An example of a tracked robot is Rugbot, the latest development of the International University Bremen (IUB), which is shown in figure 1. The early prototypes have already been used in the RoboCup 2005 competition in Osaka [23]. The robot is a complete in-house development designed especially for rescue applications [24]. The implementation is based on the CubeSystem, a collection of hardware and software components for fast robot prototyping [25][26]. A special feature of rugbot is an active flipper mechanism (figure 2) that allows to negotiate rubble piles and stairs (figures 3 and 4). Rugbots have significant computation power in form of an onboard PC and they can be equipped with a large variety of sensors.

Figure 3: going up palette

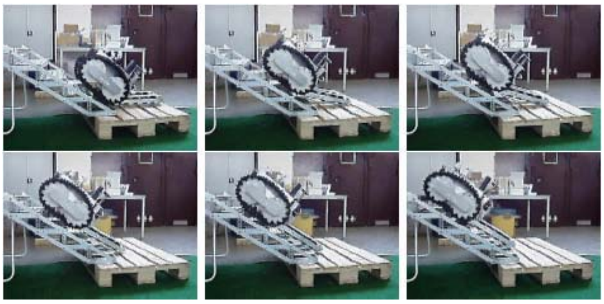
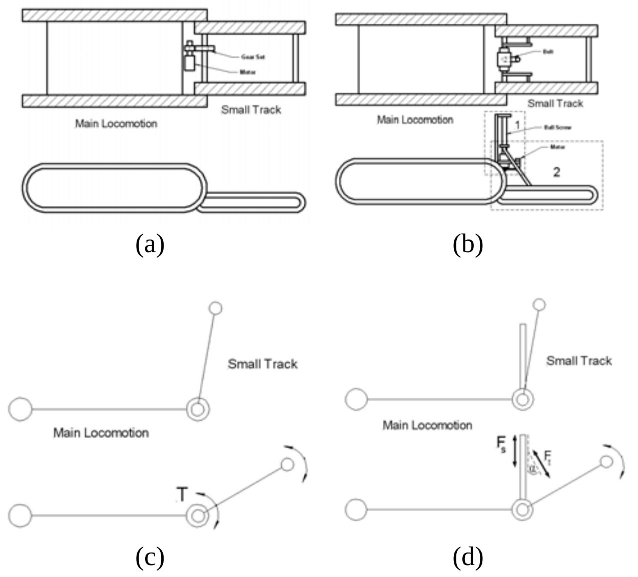


Figure 4: going up stairs

3. THE NOVEL FLIPPER MECHANISM

The tracked locomotion that has only one pair of belts will suffer from impacts, e.g. when climbing over large boulders or when it starts going down steep slopes. The common solution to this problem is to use additional tracks that can change their posture relative to the main robot body, a so-called flipper. The typical mechanism of changing a flipper posture is to directly drive the flipper joint with a spur or worm gear, a belt, or a chain drive (figure 5(a)). The great risk of this design is a broken-flipper's joint problem due to the unpredicted high force from shocks or impacts on the flipper. The problem occurs during the flipper is moved under load or the robot drives over bumps, stairs, etc. The novel flipper design presented here provides the solution for the problem. The flipper consists of a ballscrew, a passive link and a motor (figure 5(b)). The flipper requires the driving force from the motor much smaller than the classical mechanism. The novel mechanism uses the passive link and the ballscrew as the shock absorber, this means that the flipper can be easily handle without any damage from the shocks or impacts. Figure 2 shows an implementation of the flipper itself. As an example shown in figure 1, an IUB Rugbot has a main track system as the main locomotion part, while the flipper was used in case Rugbot had to overcome a stair.



(a) (b)

(c) (d)

Figure 5: A sketch of a classical locomotion system with a 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

Here, the main track system is a so-called big track, and the flipper is a so-called small track. When the robot moves around on the floor, the small track is up to minimize the footprint. The small track is pushed down to the same level of the big track when the robot has to move over a big obstacle or up/down a stair or steps. It is moved up from or down to the floor by the ballscrew. To optimize the mechanism, the following parameters have to be determined (figures 6 and 7):

- distance between the point of push or pull force on the track relative to join (A) - x
- initial length of the ballscrew relative to join (A) - y
- thrust force - Fcos(θ)
- stroke of the ballscrew to pull up the track from the floor - y_2.
- length of the mechanism (the length of the ballscrew), namely y plus y_2 - L.

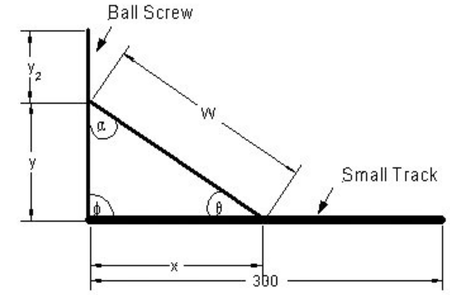
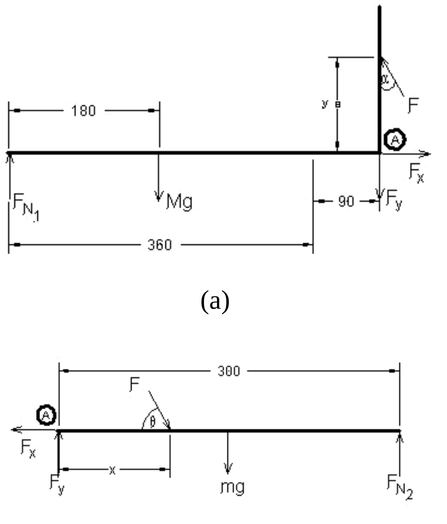


Figure 6: The core parameters in the free body diagram of the ballscrew and the small track



(a)

(b)

Figure 7: More detailed free body diagrams and parameters of (a) the main track system with the ballscrew and (b) the small track

The crucial parameters of the mechanism are the thrust force, Fcos(θ), and the stroke of movement of the ballscrew, y_2. Both parameters are analyzed following the free body diagrams in figures 6 and 7. First of all, it is assumed that the ballscrew is fixed to the robot such that it forms with the robot body and its main locomotion track as a single object as shown in figure 7(a). The small track of the flipper is a second object as shown in figure 7(b). The lengths of the big track and the small track are also important. When the flipper is pushed down, the total length must be long enough for the robot to move over the stair or the steps. The lengths in the free body diagrams are the prototype of the mechanism. From figure 7, the following equations can be derived:

$$Mg + Fy - F\cos(\alpha) = F_{N1} \tag{1}$$

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

$$mg - Fy + F\sin(\theta) = F_{N2} \tag{3}$$

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

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

$$\theta + \alpha = 90 \tag{6}$$

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

$$F_{N1} + F_{N2} = Mg + mg + F(\sin(\theta) - \cos(\alpha)) \tag{7}$$

$$F_{N1} + F_{N2} = Mg + mg \tag{8}$$

The sum of moment about A:

$$Mg \times 270 + F\sin(\alpha)y = F_{N1} \times 450 \tag{9}$$

$$F_{N1} = \frac{Mg \times 270 + F\sin(\alpha)y}{450} \tag{10}$$

$$mg \times 150 + F\sin(\theta)x = F_{N2} \times 300 \tag{11}$$

$$F_{N2} = \frac{mg \times 150 + F\sin(\theta)x}{300} \tag{12}$$

Rearrange (8) with (10) and (12), the thrust force is

$$F = \frac{225}{\dfrac{\sin(\alpha)x\tan(\theta)}{450} + \dfrac{\sin(\theta)x}{300}} \tag{13}$$

The thrust force is determined base on the weights of the robot and the flipper (Mg and mg), the distance x, and the angles between the link and the ballscrew (α) and between the link and the small track (θ). Equation 13 shows the final result after replace the weights of the robot and the flipper. With a numerical analysis, different variations of these parameters can be computed. For Rugbot, the first parameter that should be specified is the length of the mechanism (L), namely y plus y_2.

Then, the values of x, y and W are used to calculate the stroke y_2 by the free body diagrams of figures 6 and 8.

From figure 6,

$$W = \frac{x}{\cos(\theta)} \tag{14}$$

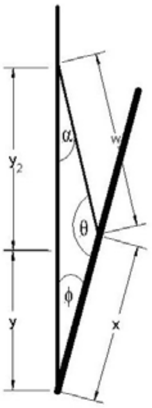


Figure 8: The free body diagram of the ballscrew and the small track when the flipper is moved up

Given a minimum angle of 10 degrees for α when the flipper is pulled up as shown in figure 8, the relations between x, y, W and y_2 are

$$\alpha = \arcsin\left(\frac{x \times \sin(10)}{W}\right) \tag{15}$$

$$y_2 = \frac{W \times \sin(170 - \alpha)}{\sin(10)} - y \tag{16}$$

With the height limit of the robot, all parameters can be analyzed. Table 1 shows the result of variation values for the prototype system. The novel mechanism provides the durable flipper that 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 as shown in figures 3 and 4.

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

Table 1: Parameter of the small track based on the component length, L

4. CONCLUSION

Construction sites are very dangerous working environments. Here we extended the idea of rescue robots to consider their use for construction site safety. One core aspect for this application is the locomotion system of the robots. It has to provide sufficient payload, it must be energy-efficient, and it nevertheless must be able to climb obstacles and stairs while having a small footprint to go through doorways and narrow passages. Adjustable support tracks are a common concept for changing the footprint of a rescue robot. Here, a novel mechanism of 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 that lead to a sturdy design. The mechanism is implemented on the so-called Rugbot type of robots from IUB. They are very mobile, equipped with many sensors, and low cost; they are hence a potential platform for large scale use in the construction industry.

REFERENCES

[1] Hisanori Amano. A vertically moving robot able to grip handrails for fire-fighting. Advanced Robotics, 16:557 560, 2002.

[2] Chia-Fen Chi, Tin-Chang Chang, and Hsin-I Ting. Accident patterns and prevention measures for fatal occupational falls in the construction industry. Applied Ergonomics, 36:391 – 400, 2005.

[3] European Agency for Safety and Health at Work. Issue 15 - accident prevention in the construction sector. OPOCE Catalog number: TE3501287END, 29 March 2001.

[4] F. Hardarsson. Locomotion for difficult terrain. Technical report, Mechatronics Lab, Dept. of Machine Design, 1997.

[5] Health and Safety Executive. Construction fire safety. Free Leaflets - Construction, March 2005.

[6] Douglas Page. New device may fight tunnel fires by remote control. Fire Chief. Feb 1, 2000. http://firechief.com/mag/firefighting_new_device_may/index.html

[7] FIRE CHIEF STAFF. Robotic insects could be newest fire/rescue tool. Fire Chief. Feb 1, 2000. http://firechief.com/mag/firefighting_robotic_insects_newest/index.html

[8] NASA's Aeronautics Mission Directorate. High-tech fire fighting. NASAexplores, December 12, 2001. http://www.nasaexplores.com/show2_articlea.php?id=01-091

[9] Society of American Foresters. Nasa tests firefighting robot plane. October 2001 issue of The Forestry Source. http://www.safnet.org/archive/nasa1001.

[10] Nobuo Kimura. Development of rescue robotic systems for both daily and emergency use. In ‘Robots in Unstructured Environments’, 91 ICAR., Fifth International Conference on Advanced Robotics, 1991 1: 309 – 314. IEEE Press, 1991.

[11] A. Kobayashi and K. Nakamura. Rescue robot for fire hazards. In Proc. of International Conference on Advanced Robotics, pages 91 – 98, 1983.

[12] Helen Lingard. The effect of first aid training on Australian construction workers’ occupational health and safety motivation and risk control behavior. Journal of Safety Research, 33:209 – 230, 2002.

[13] Ger Maas and Frans van Gassel. The influence of automation and robotics on the performance construction. Automation in Construction, 14:435 – 441, 2005.

[14] Kazuyoshi Miyazawa. Fire robots developed by the Tokyo fire department. Advanced Robotics, 16:553556, 2002.

[15] A. Nishi and H. Miyagi. Mechanism and control of propeller type wall-climbing robot. In ‘Advanced Robotic Systems and the Real World’, IROS ’94. Proceedings of the IEEE/RSJ/GI International Conference on Intelligent Robots and Systems ’94, pages 1724 – 1729. IEEE Press, 1994.

[16] N. Shiroma, Yu huan Chiu, T. Kamegawa, and F. Matsuno. Development of rescue robotic systems for both daily and emergency use. In First IEEE Technical Exhibition Based Conference on Robotics and Automation, 2004, pages 85 – 86, IEEE Press, 2004.

[17] S. Tadokoro, T. Takamori, S. Tsurutani, and K. Osuka. On robotic rescue facilities for disastrous earthquakes - from the Great Hanshin-Awaji (Kobe) earthquake. Robotics and Mechantronics, 9:46 – 56, 1997.

[18] Satoshi Tadokoro, Toshi Takamori, Koichi Osuka, and Saburo Tsurutani. Investigation report of the rescue problem at Hanshin-Awaji earthquake in Kobe. International Conference on Intelligent Robots and Systems, 3:1880 – 1885, 2000.

[19] C. M. Tam, S. X. Zeng, and Z. M. Deng. Identifying elements of poor construction safety management in China. Safety Science, 42:569 – 586, 2004.

[20] S. Thomas Ng, Kam Pong Cheng, and R. Martin Skitmore. A framework for evaluating the safety performance of construction contractors. Building and Environment, 40:1347 – 1355, 2005.

[21] Loughborough University and UMIST. Causal factors in construction accidents. HSE BOOKS, Norwich, first published 2003 edition, 2003.

[22] J. Y.Wong. Theory of Ground Vehicle, 3rd edition, chapter 4.5. John Wiley and Sons, Inc., 2001.

[23] Andreas Birk, Stefano Carpin, Winai Chonnaparamutt, Viktoras Jucikas, Hamed Bastani, Ivan Delchev, Ivan Krivulev, Seongchu Lee, Stefan Markov, and Andreas Pfeil. The IUB 2005 rescue robot team. In Itsuki Noda, Adam Jacoff, Ansgar Bredenfeld, and Yasutake Takahashi, editors, RoboCup 2005: Robot Soccer World Cup IX, Lecture Notes in Artificial Intelligence (LNAI). Springer, 2006.

[24] Andreas Birk and Stefano Carpin. Rescue robotics - a crucial milestone on the road to autonomous systems. advanced Robotics Journal, 20(5), 2006.

[25] Andreas Birk. Fast robot prototyping with the CubeSystem. In Proceedings of the International Conference on Robotics and Automation, ICRA’2004. IEEE Press, 2004.

[26] Andreas Birk, Holger Kenn, and Thomas Walle. On-board control in the RoboCup small robots league. Advanced Robotics Journal, 14(1):27 – 36, 2000.