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Study on the Mobility of Service Robots

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Abstract

The major characteristics of robots can be divided into several categories ranging from mobility to autonomy. The mobility of service robots is essential and fundamental to commercial and scientific progress. The rapid development of practical service robots depends on our decision which are the most efficient and affordable kinds of locomotion. The selection of the best locomotion, however, is not simple and easy, since the boundaries of robot working areas cannot always be defined clearly. This study emphasizes the usefulness of humanoid type service robots as general service robots, and concentrates on finding the most appropriate means of locomotion for a particular workspace. Several forms of robot locomotion were considered in three types of workspaces, and compared analytically. The results showed that three/four-wheeled robots were best suited to work in a large office or factory. Bipedal robots were suited to work in a small office or home, and quadruped robots were suited to work in outdoors. As a general alternative, bipedal locomotion seems to be the most adaptable form of locomotion for general service robots.

Keywords: mobile robot, mobility, service robot, bipedal robot, humanoid, wheeled robot

1. Introduction

Robots can be roughly divided into two categories: industrial robots and service robots. A few years ago, most robot applications were built into industrial robots, which are related to industries and manufacturing. Industrial robots are only required to make simple and repetitive motions in restrictive and standardized environments. Because of this advantage, the field of industrial robots has grown fast. In contrast to industrial robots, service robots are required to make complex and autonomous motions in various environments. As a result, the field of service robots has had challenging problems, and therefore, they couldn't grow quickly. Service robots, however, can be applied to people's living and working spaces, such as homes, offices, factories, and so on. The paradigm of robotics is moving from a specific industrial technology to the consumer, home, and service markets [1].

Various service robots have been developed and demonstrated in many laboratories and companies [2]-[9], yet these robots could not easily occupy people's living spaces until now. Only a few service robots have been commercialized and put into use, such as Sony's AIBO [2] and iRobot's RoombaTM [3]. Because these practical service robots only need a few simple functions to perform their given tasks of moving and cleaning, these robots have been successful. Most service robots, however, usually need high-level intelligence and autonomous control. They should be able to interact with humans in natural

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ways, go to specified places, behave in a human-like manner, perform manipulation tasks, recognize the surrounded environment, and so on [10]-[15]. With these necessary functional abilities, service robots can be interactive assistants for humans.

In order to commercialize the service robots, a study on the development of the standardization of service robot should be conducted. In this paper, various kinds of service robots are studied, and an alternative development of service robot is suggested as a solution for commercialization of service robots. After the alternative form of service robot is suggested, the most appropriated locomotion of the service robot is considered. In contrast to the specialized service robots, the general service robots can have various functional abilities. Humanoid robot is one of the most representative forms of general service robot, and performs many tasks using two manipulative arms and several instruments. In this paper, humanoid robot is suggested as an alternative development form of service robot, and the locomotion of humanoid robot is considered carefully. For service robots, mobility is essential to perform tasks in rough and complex environments. Service robots can have several types of locomotion: wheeling, walking, hopping, and so on. Researchers must ponder what type of locomotion to select when considering the primary tasks given to robots. In addition, they must consider the merits and faults of each method.

Compared to industrial robots, service robots can be divided into many categories. Each type of service robot has several dedicated and specialized operational abilities. Their abilities and uses are described in Section 2, and humanoid type general service robots are nominated as an alternative solution for convergence of service robots. After robot's workspace and locomotion are considered in Section 3, the mobility of robots is compared in Section 4. Based on this comparison, Section 5 selects the most affordable locomotion for general service robots, and Section 6 concludes the paper.

2. Convergence of Service Robots

Recent advances in artificial intelligence and autonomous control have caused researchers to put service robots in the living spaces of humans. Many researchers focused on the technologies for robotic appliances. Despite their effort, however, the industrial development of service robots is still growing slowly. This is because service robots do not have standardized development platform, in spite of their necessary of diverse functional abilities. On this occasion, investigation of efficiency and affordability to develop new, innovative, and basic service robot platform, is required.

Service robots perform various tasks, from guidance to serving, and require diverse abilities dedicated to their tasks. Developing all these abilities is difficult and costly. It is only rational to consider the most important and essential ones first. Most service robots share several essential and common abilities. For example, they physically interact through manipulation, recognize humans and objects through vision and sensory processing, and move around through locomotive faculty.

In contrast with industrial robots, most service robots should be able to move around the living spaces of humans and serve as their assistants. Indeed, improvements to mobility are essential and important for the commercialization and industrialization of service robots because service robots are required to make complex and autonomous motions in various environments. For the selection of their efficient and appropriate mobility mechanisms, the major tasks and roles of robots must be considered and evaluated first. After that, a new and innovative direction for service robots can be clear.

2.1.1. Categories of Service Robots

As previously stated, service robots are divided into several categories, and each service robot has its respective tasks. To achieve these tasks successfully, each robot must be equipped with an appropriate mobile mechanism. Thus, the types of service robots have to be considered according to their given tasks first, and set the boundaries of the research. Fig. 1 describes the assortment of service robots [4]-[7], [16]-[29].

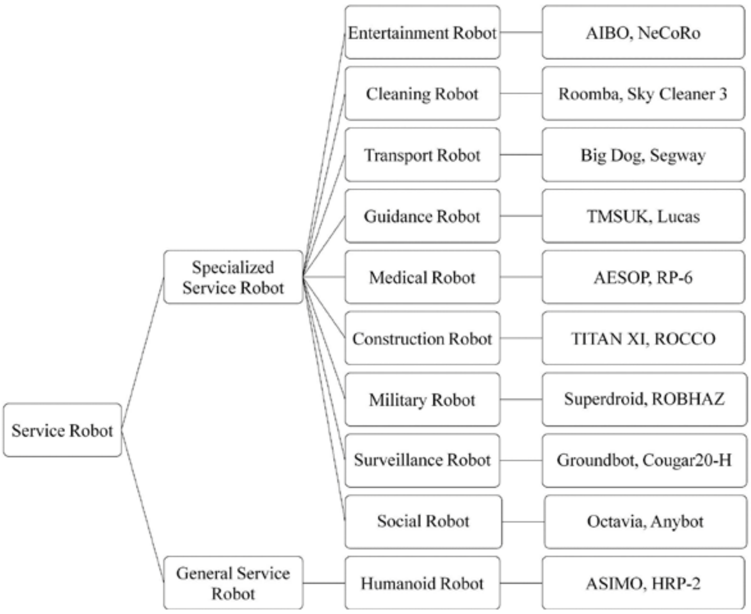


Fig. 1 Categories of service robots

Service robots can be separated into specialized robots and general robots. The specialized robots have various functions, from entertainment to construction, and they have unique tasks. Sony's AIBO entertains humans, iRobot's RoombaTM cleans the floor, BostonDynamics's BigDog transports heavy items, and so on. Such specialized robots only rarely can change their functional ability to perform other tasks. In contrast, general service robots can handle a much larger range of tasks. Humanoid robots are a typical kind of general service robot. Usually, they are not developed for just one or two aims. The humanoid robot, indeed, can perform more tasks than specialized service robots can.

2.1.2. Convergence of Service Robots Using Humanoid Robots

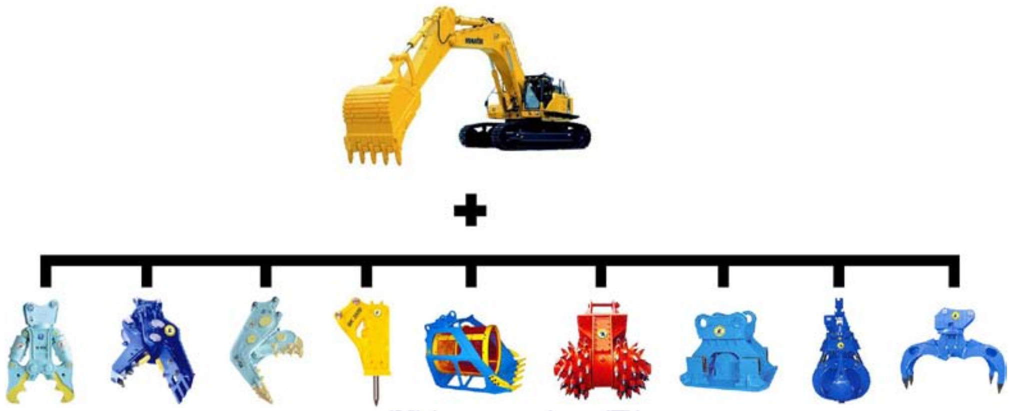
Humans want robot to assist them in their daily lives as soon as possible. However, developers face the problem of creating service robots with economical efficiency. Low production cost and high usefulness are significant factors for commercialization and industrialization, and meeting these factors is imperative for the development of service robots. Humanoid robots can be a good solution to meet them.

In the case of specialized service robots, several robots must be involved for one complex task, and cooperate with each other. All these robots must of course be equipped with parts for locomotion, control, interface, power, and so on. It is a wasteful use of resources. In addition, several service robots must often share the same space with others. They need more working space, longer working hours, and more difficult cooperative control methods than one service robot does. In contrast with these, general service robots including humanoid robots can finish most given tasks alone. The major advantage of the humanoid robots is their convergence of specialized service robot technologies.

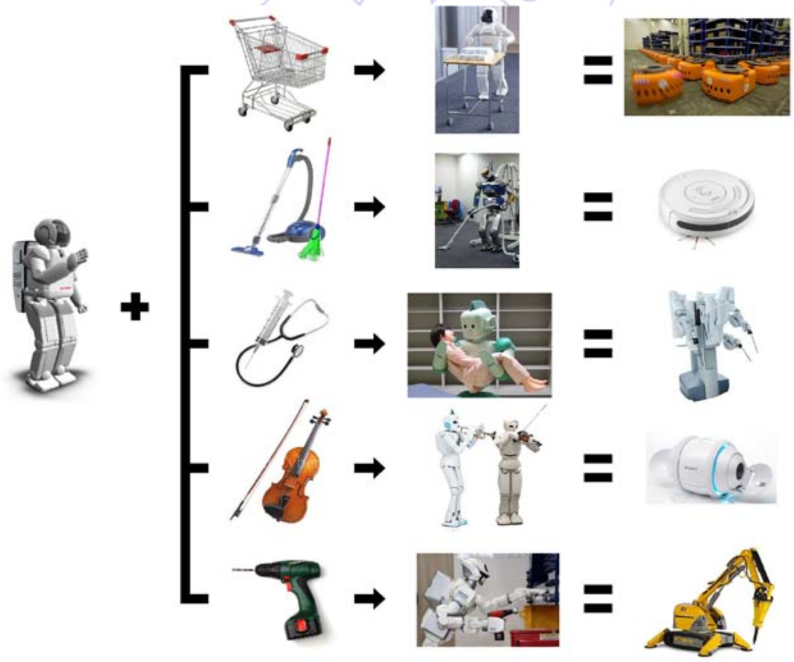
The combination of excavator and its attachments is a good commercialized example of convergence. With several attachments, one excavator can perform various tasks as shown in Fig. 2(a). Similarly, humanoid robots can perform most tasks using two manipulative arms and several instruments, and can be utilized everywhere specialized service robots was, as shown in Fig. 2(b). One humanoid robot having two arms can of course replace several specialized service robots. Thus, the development of humanoid robots can decrease production cost and increase usefulness of service robots. As a result, humanoid robots can be a good solution for commercialization and industrialization of service robots.

Humanoid robots usually have one head, two arms, and two legs. Two arms are efficient and affordable for the convergence of service robot functions, as previously stated, and one head is essential to camera image capture and processing for environment and object recognition. Two legs, however, are not essential to general service robots. Some humanoid robots can have alternative forms of locomotion, such as wheeled locomotion. For example, NASA's Robonaut B [30] and JSK's HRP-2W [31], whose upper bodies are humanoid type and whose lower bodies are wheels, have already developed. Therefore, which type of locomotion is efficient and appropriate for humanoid robots that have one head and two manipulative arms, should be considered carefully.

Mobility of robots is dependent on their workspaces. After looking at the workspaces of service robots first, the mobility of each service robot can be compared methodically.



(a) Excavator and its attachments



(b) The usefulness of humanoid robots

Fig. 2 Convergence of service robots using humanoid robots

3. Consideration of Workspace and Robot's Locomotion

3.1. Categories of Workspace

Industrial robots are usually attached to a fixed surface, and even if they need to move, the workspace is restrictive and unchanging. In contrast with this, service robots need to move around various human living environments. Their mobility is essential factor that is closely related to their workspaces, which must be the first consideration. Workspaces can be divided into the following three types.

3.1.1. Workspace Type 1: Large, Well-constructed Building

Usually, these spaces are where humans work, and are furnished with elevators, escalators, and slopes. Using these avenues to move through building levels, service robots can move to most places to accomplish their tasks. Even if there are few doorsills and stairs obstruct the movement of robots, elevators, escalators, and slopes still can help to avoid these obstructions. Mobility in this work space type is generally the best of the three.

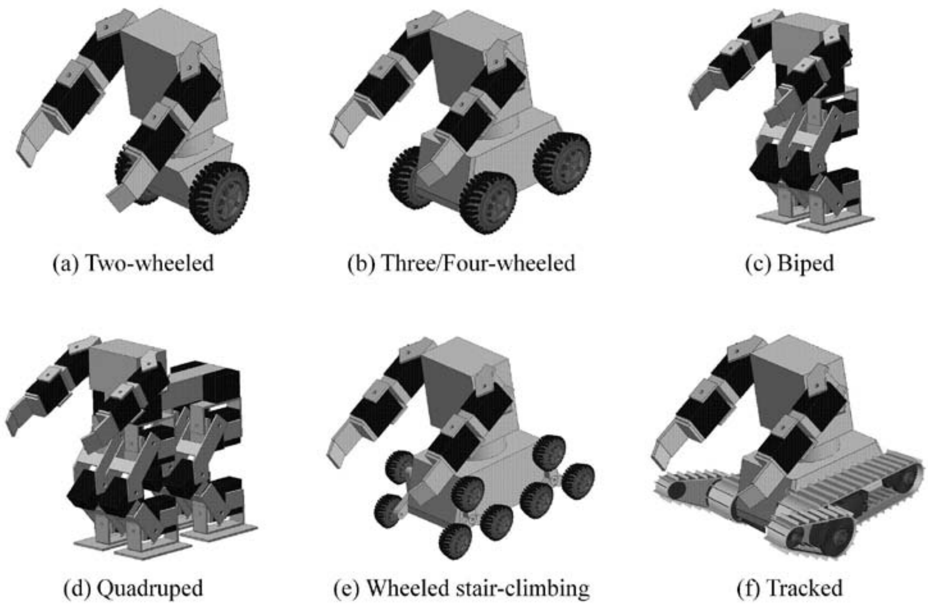
3.1.2. Workspace Type 2: Small, Variably Structured Buildings

These spaces are not usually furnished with robot-friendly facilities, such as elevators, escalators, or slopes. Therefore, robots must be able to go up and down stairs. In addition, these environments usually have many doorsills and small obstacles to go over. Type 2 is worse than Type 1 for robots. However, the overall ground surface is flat and its conditions are at least generally good.

3.1.3. Workspace Type 3: Outdoors

This type of workspace has the most various working conditions. Robots must be able to go up and down stairs, move on uneven terrain. In spite of these rough operating conditions, they must be able to operate reliably and stably.

3.2. Categories of Robot's Locomotion



Structure sketch

Fig. 3 Basic conception of robots with various locomotion styles

Locomotion of service robots can be roughly divided into six categories: two-wheeled, three/four-wheeled, biped, quadruped, wheeled stair-climbing, and tracked. This assortment is based on a paradigmatic set of practical service robot examples [32]-[38]. In fact, many other kinds of locomotion, besides the above-mentioned categories, have been developed, such as underwater robots and flying robots, but only general, practical, and popular locomotion for the common applications of service robots will be concerned primarily. Improper forms of locomotion for the humanoid robots, such as hoppers, crawlers, and sliders, are ignored, and similar forms are conflated.

Fig. 3 shows representative forms of robots with respective locomotion [5], [20], [25], [34], [36]-[37], [39]. The wheeled stair-climbing robots and tracked robots are designed to supplement the insufficient mobility of conventional wheeled robots. The wheeled stair-climbing robots are designed to be able to go up and down stairs, and the tracked robots to overcome various obstacles and uneven terrain.

4. Mobility Comparison of Service Robots

Previously, the categories of workspaces and locomotion are enumerated. Each workspace may have microenvironments with various configurations of floors, ground, and transitional facilities such as slopes, escalators, elevators, doorsills, and stairs; and service robots must be able to move around on these environments through affordable locomotive faculty. Table 1 describes the comparison results between six kinds of robot locomotion for six environments [25]-[27], [30]-[36].

Table 1 Locomotion for Each Environment

Locomotion	Environments					
	Even Ground	*Uneven Ground*	*Slope*	*Escalator / Elevator*	*Doorsill*	*Stair*
Two-Wheeled	+	−	+	−	○	−−
Three/Four-Wheeeled	++	+	○	+	+	−−
Biped	+	+	+	+	+	+
Quadruped	++	++	++	+	++	+
Wheeled Stair-climbing	++	+	○	+	++	−
Tracked	++	++	○	+	+	−

'++': very good; '+': good; '○': normal; '−': poor; '−−': very poor

4.1. Even Ground

Most forms of locomotion have very good mobility on even ground. Most robots, indeed, maintain stability tolerably well. Two-wheeled and bipedal robots merely need a balance control not to fall down.

4.2. Uneven Ground

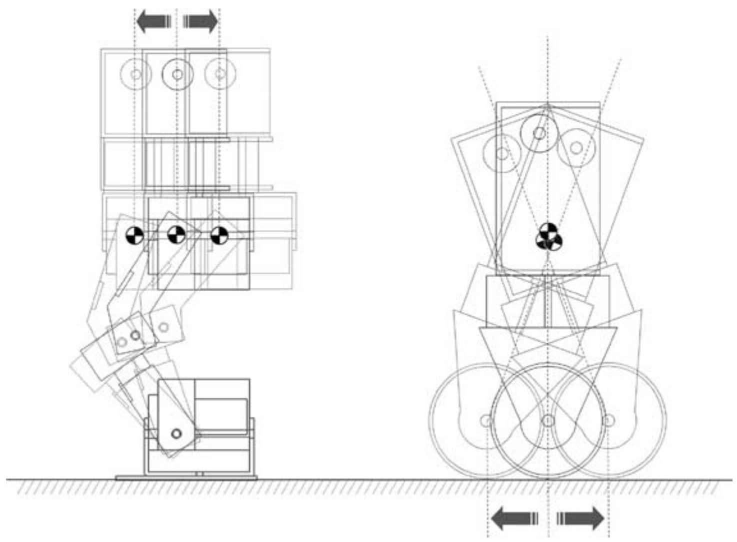


Fig. 4 Comparison of balance control between two-wheeled and bipedal robots

Wheeled locomotion has the most trouble with uneven ground, because wheeled robots can easily slip and get out of control. Especially, two-wheeled robots have the worst mobility, because they are modelled as inverted pendulums and must be controlled at unstable equilibrium point of these models. Not only two-wheeled robots, but bipedal robots are also modelled as inverted pendulums [40], and they must always compensate their balance in order not to fall down. The bipedal robot, however, is less affected by uneven ground and it's also stable on even ground. In contrast with the bipedal robot, the two-wheeled robot must roll on its wheels, changing the contact points between the wheels and ground for the body balance, as shown in Fig. 4. When the adhesion coefficient of wheel, which is dependent on the ground conditions and the value of the wheel slip, is low, the wheeled robot can easily slipped and lost its balance.

4.3. Slopes

The two-wheeled robot and the bipedal robot cannot keep balance without continuous balance controls. With slopes, however, they have more mobility than the others do. The stability, when they are climbing up the slope with acceleration $a(m/s^2)$, is analyzed and described in Appendix 2.

4.4. Escalators/Elevators

The escalator and elevator are the most common moving conveniences in indoor and outdoor environments, and robots should be able to share these facilities with humans. Using these facilities creates rigid constraints on body dimensions and speed. The robot, indeed, must be small enough to share these limited spaces with humans, and the robots should be able to pass the open door of an elevator in time and ride on the escalator safely. Because of these constraints, the two-wheeled and quadruped robots have some disadvantages. The two-wheeled robot can hardly keep its balance in strictly limited spaces, such as the balustrade panels of escalators; quadruped robots, which are difficult to be designed small, need to make many efforts to ride on and operate in these narrow conditions. If the robot overcomes the limitation caused by small size of space, the mobility is similar to one on the even ground. However, most robots with three/four wheeled, quadruped, wheeled stair-climbing and tracked robots have large body dimensions.

4.5. Doorsills

Human living spaces have various small obstacles, such as doorsills. When robots cross over, some undesirable movements result, and these disturbances destabilize robots. In particular, two-wheeled and tracked robots are less stable than others are. The two-wheeled robot with just two wheels contacting the ground is difficult to control if one or both wheels are lifted off the doorsill, and the front end of a tracked robot must be stopped from crashing into the ground when it climbs down the doorsill [41].

4.6. Stair

The most troublesome environment to overcome for service robots is climbing up and down the stairs stably. The conventional two-wheeled robots and three/four-wheeled robots cannot climb up stairs at all. Moreover, according to the angle of the drive, wheeled stair-climbing and tracked robots can slip off easily. This is because the wheeled stair-climbing robot is highly dependent upon the shapes and sizes of stairs [35], [36], and the tracked robot contends with minor lateral friction at the line contacts of the stair edges. Fortunately, the legged robots, such as the bipedal and quadruped robots, are independent on the stairs and do not slip down.

5. Affordable Service Robot Systems

The environments of three workspaces range from even ground to stairs. Comparing the mobility of each environment, economically suitable and affordable robot locomotion for each workspace can be selected.

5.1. Workspace Type 1

This workspace has the best moving and working conditions for service robots. The minimum requirement is ability to move around multi-story spaces using escalators, elevators, and slopes. The three/four-wheeled, bipedal, wheeled stair-climbing, and tracked robots generally qualify. In this situation, lower cost may outweigh considerations of mobility. The three/four-wheeled robot has enough mobility and the lowest production cost. This form of locomotion is the most affordable to this workspace. In fact, many service robots are designed with three or four-wheeled locomotion these days [21], [22].

5.2. Workspace Type 2

Robots in this workspace should be able to go up and down stairs. Bipedal and quadruped robots have more mobility than the others on the stairs. The quadruped robot, however, cannot operate freely in narrow spaces such as escalators and elevators because of the constraints on big body size. In fact, bipedal locomotion is the best solution for the movement of service robots. Furthermore, the humanoid robots with bipedal locomotion can pass through much more complex and rugged areas than others can [42]-[44].

5.3. Workspace Type 3

This space has more various and uneven environments than the others, but has a much larger action space. Thus, the quadruped robot has more advantages and utility than bipedal robots. For example, Boston Dynamics's BigDog has good mobility and transport capacity in outdoor [31].

5.4. Advanced Consideration

The proper mobility of service robots is dependent on workspace. Workspaces and their locomotion requirements are of three types. The results showed that three/four-wheeled robots were best suited to work in a large office or factory, bipedal robots were suited to work in a small office or home, and quadruped robots were suited to work outdoors. However, the types of workspace could not be separated clearly, and the locomotion of each robot could not be selected formally. Some places (among Type 1 workspaces) can be approached only by the stairs or ladders, and a quadruped robot carrying some heavy burden sometimes can go into building of Type 2. A confounding factor is that a robot in one workspace sometimes needs to perform like robots in other workspaces. This embarrassing situation needs to be avoided. The most general and universal forms of robot locomotion, such as bipedal locomotion, should be considered in such cases.

A specially dedicated service robot system is certainly needed, but major research on service robots would be directed at the general types. Among all the forms of robot locomotion, bipedal locomotion is the most stable and adaptable, as shown in Table 1. Furthermore, bipedal robot has more advantages than the others do, such as wider reach [45], higher operational ability in narrow [42], complex, or height-limited areas [43], and high braking power in an emergency [46]. These advantages of bipedal robots will be addressed below.

Service robots, as assistants to humans, should be able to cooperate with humans and manipulate an object. Thus, the service robot should be tall enough [27]. In addition to this constraint of height, the constraints of width and length are important to robots, which have to move around narrow places. In short, service robots need to be tall enough and have a small enough width and length. These factors are, however, usually in inverse proportion to the mobility of movement.

Service robots share the workspace with humans. They must be able to stop immediately in order not to hurt humans in case of emergency. Fig. 5 illustrates the braking of wheeled robot. When coefficient of friction of wheel is high enough and r′ is approximately the same as r, friction force F can be replaced with equivalent inertial force Fe, and kinetic energy gives

$$
\begin{aligned}
E_k &= \frac{1}{2}mv^2 = \int_{\pi/2-\theta}^{\pi/2} rF_e \sin\phi d\phi \\
&\le \int_{\pi/2-\theta}^{\pi/2} rmg\cos\phi d\phi = mg\left(\sqrt{h^2+\ell^2}-h\right)
\end{aligned} \tag{1}
$$

From this equation, the maximum velocity of wheeled robot according to body dimensions (h, λ) can be derived:

$$
v \le \sqrt{2g\left(\sqrt{h^2+\ell^2}-h\right)} \tag{2}
$$

and the relation of them is shown in Fig. 6. The high maximum velocity means high braking power. For the enough braking power, the body length should be long enough and have height as small as possible, as indicated in Fig. 6. These conditions, however, are opposite to the constraints on body dimensions of service robots.

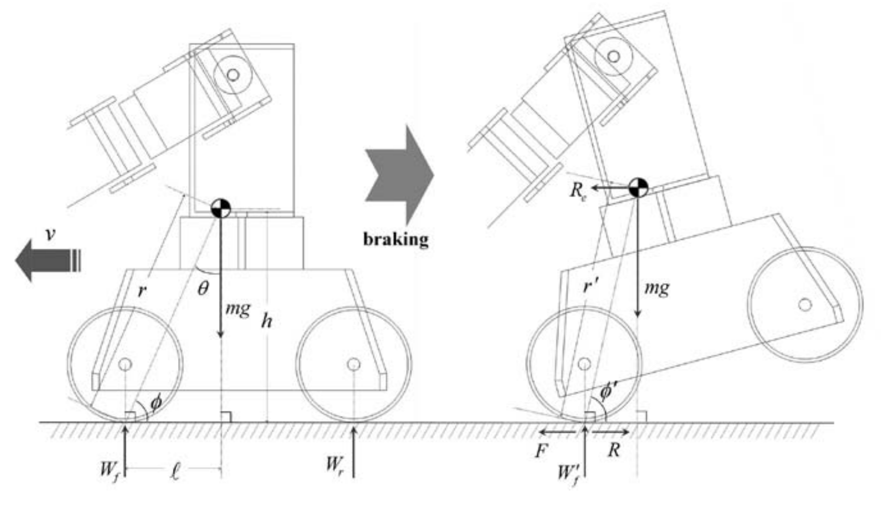


Fig. 5 The braking of wheeled robot

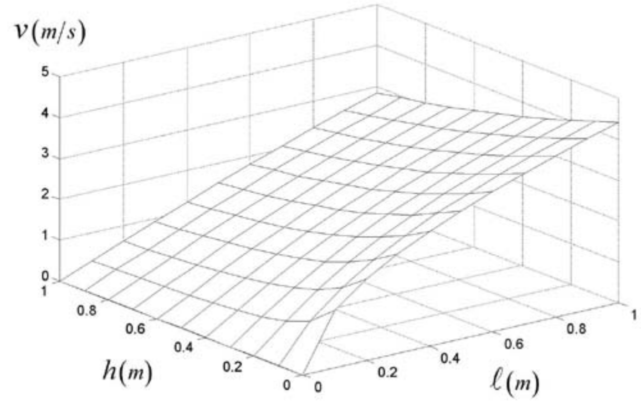


Fig. 6 The maximum velocity vs. height and length

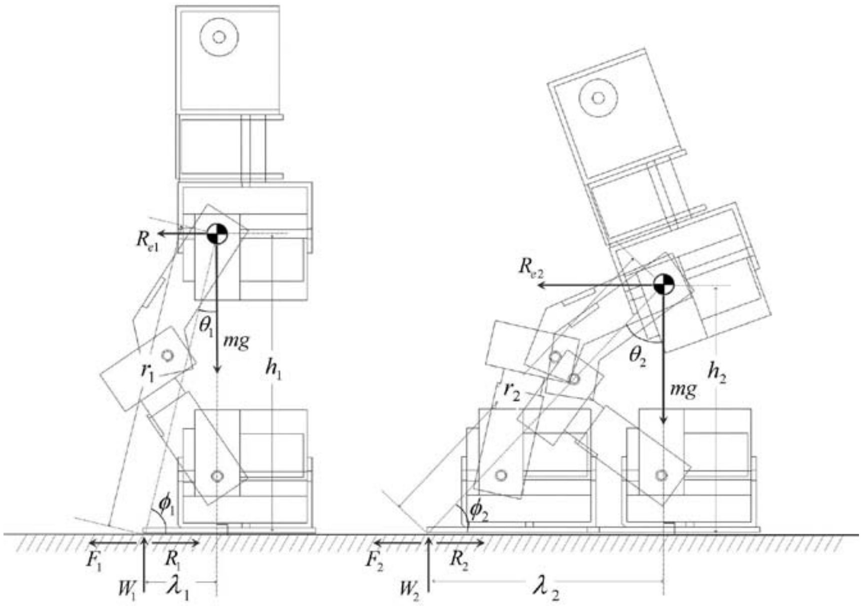


Fig. 7 The braking of bipedal robot; left: in the ordinary situation, right: in emergency

In contrast, bipedal robots can have more braking power than service robots. They normally have smaller body length λ_1 and larger height h_1 than wheeled robots, as shown in Fig. 7. However, according to the change of posture, the term λ_1 can increase into λ_2 and h1 decrease into h_2. The long body length λ_2 and short height h_2 produce high maximum velocity in (2).

6. Conclusion

In this paper, the mobility of service robots is addressed. Mobility is an important requirement of service robots, and the affordability of the locomotion method must be carefully considered for the successful commercialization and industrialization of service robots. The workspace of humans can be divided into three categories, and each service robot of each workspace has respective locomotion method. However, according to the primitive purpose, general service robots should be able to perform most tasks given to them anywhere. Bipedal robots have more advantages as general service robot, such as space saving, adaptability to most environments, and braking power. These advantages can help to bring greater commercial and scientific success in the field of service robots.

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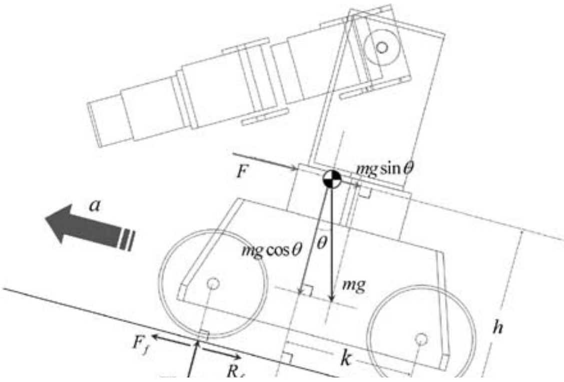
Appendix 1

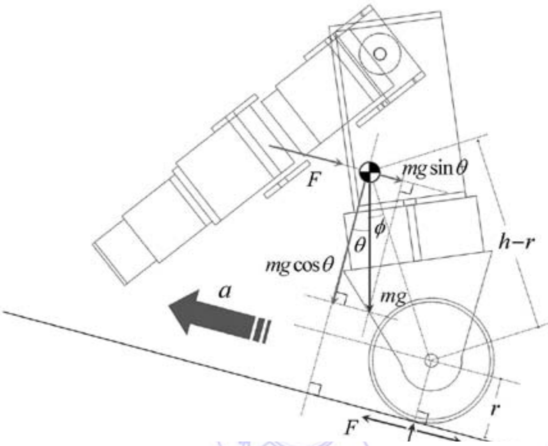
NOTATION

ν	Velocity of robot
r	Radius of wheel
m	Total mass of robot body
g	Gravity acceleration
h	Height of robots
θ	Angle of slopes
ø	Lean angle of body of two-wheeled robot
a	Acceleration of robots
λ, λ1, λ2	Maximum length between contact points of wheel or foot
F	Tractive force
Fe, Fe1, Fe2	Equivalent inertial forces of F
μ	Coefficient of Friction of wheel and foot
R, Rf, Rr	Resistance forces
W, Wf, Wr	Weights on wheels or foot

Appendix 2

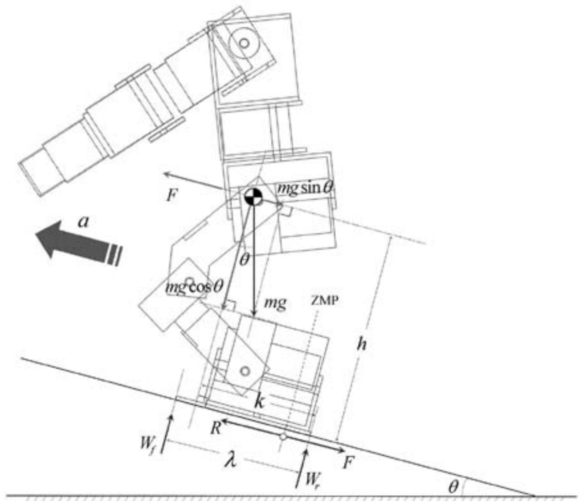


(a) Four-wheeled



(b) Two-wheeled

Fig. A1 Schematics of robots on the slope



(c) Biped

Fig. A1 Schematics of robots on the slope (Continued)

Fig. A1 shows schematics of robots on the slope, and Fig. A2 describes the possible maximum acceleration of robots verses the angle of slope.

FOUR-WHEELED:

The normal forces of the front and the rear wheels are given by

$$W_f = \left(kmg\cos\theta - hmg\sin\theta - mah\right)/\ell \tag{A1}$$

$$W_r = \left(\left(\ell - k\right)mg\cos\theta + hmg\sin\theta + mah\right)/\ell \tag{A2}$$

and if the robot is designed with four wheel drive, the friction force of wheels is given by

$$R = R_f + R_r = \mu mg\cos\theta \tag{A3}$$

The normal forces of wheels must be positive in order not to be overturned, and robot must not be slipped because of the low friction force: Wf, Wr ⩾ 0 and R ⩾ ma. Using this constrains in (3)-(5) gives:

$$-g\left(\frac{\ell - k}{h}\cos\theta + \sin\theta\right) \le a \le g\left(\frac{k}{h}\cos\theta - \sin\theta\right) \tag{A4}$$

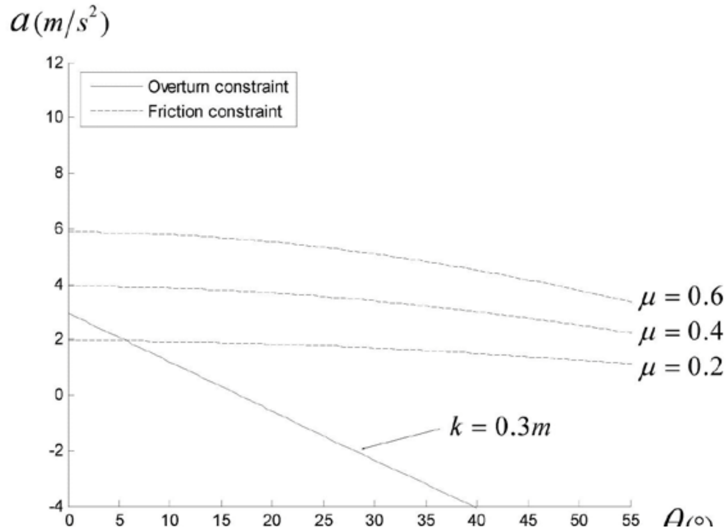
$$a \le \mu g\cos\theta \tag{A5}$$

Fig. A2(a) shows the maximum acceleration according to (6) and (7). The lower acceleration is only available, as the slope steepens and the coefficient of friction decreases.

TWO-WHEELED:

In contrast to the four-wheeled robot, the mobility of two-wheeled robot only dependent on the friction force of wheels. Adjusting the lean angle of body ø, the robot can accelerate to *a(m/s²)* stably.

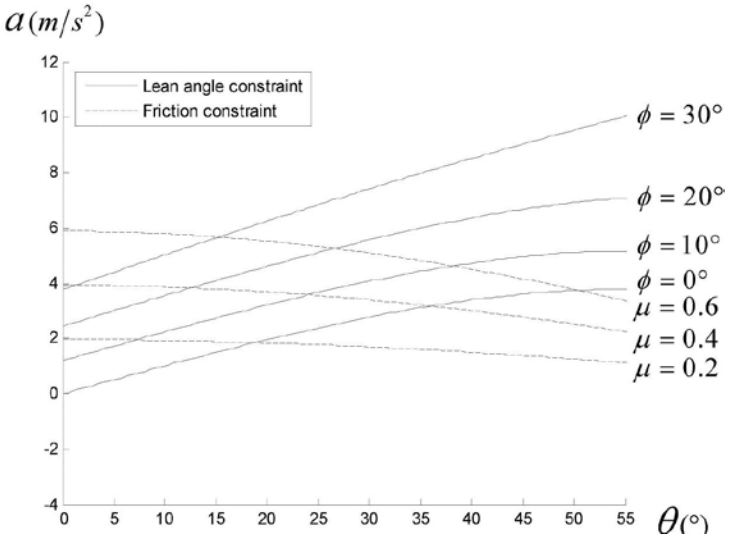
$$a = g\left(\frac{(h-r)\sin(\theta+\phi)\cos\theta}{(h-r)\cos(\theta+\phi)+r} - \sin\theta\right) \tag{A6}$$



(a) Four-wheeled

Fig. A2 The maximum acceleration versus the angle of slope (*h=1m, g=9.8m/s2, λ=0.6m*)

Fig. A2(b) describes the acceleration values for the stable equilibrium condition, according to the lean angle of body ø. Leaning to the front, the two-wheeled robot can increase the acceleration within the constraint of friction constraint.



(b) Two-wheeled

Fig. A2 The maximum acceleration versus the angle of slope (*h=1m, g=9.8m/s2, λ=0.6m*)

BIPED:

This type of locomotion is based on the pushing of leg, not on the rolling of wheel. Pushing the ground, the center of mass will be pushed to the front by reaction. The normal forces of the front and the rear of foot are given by

$$W_f = (kmg\cos\theta - hmg\sin\theta + mah)/\ell \tag{A7}$$

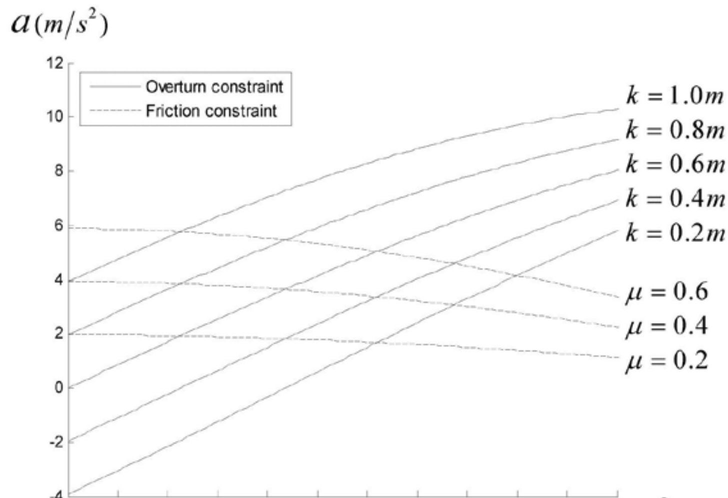
$$W_r = ((\ell - k)mg\cos\theta + hmg\sin\theta - mah)/\ell \tag{A8}$$

and the friction force of foot is given by

$$R = \mu mg\cos\theta \tag{A9}$$

Similar to the four-wheeled robot, the bipedal robot must satisfy W_f, $W_r \geq 0$.

$$-g\left(\frac{k}{h}\cos\theta - \sin\theta\right) \leq a \leq g\left(\frac{\ell - k}{h}\cos\theta + \sin\theta\right) \tag{A10}$$



(c) Biped

Fig. A2 The maximum acceleration versus the angle of slope (*h=1m, g=9.8m/s2, λ=0.6m*)(Continued) and the constrain from the friction force is the same as that of others. The result for these constraints is described in Fig. A2(c), and it seems similar to that of two-wheeled robot.