2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Development of Falcon III: Terrain-Adaptive Body-Stabilizing Three-Wheeled Vehicle

Ewerton Ickowzcy, Takeshi Aoki, and Shigeo Hirose

Abstract— **With the appearance of many personal vehicles developed for urban environments, it seems pertinent to address the development of off-road personal vehicles as well. This paper discusses this exact topic, and proposes a three-wheeled configuration which stabilizes the horizontal posture of the vehicle's driver in rough terrain. The merits of such a machine are examined; in addition, a mechanism here called *sliding-rod-end* is introduced, and the reasons for its use instead of regular rod ends are explained. A full-scale prototype of the machine was built and is briefly presented.**

I. INTRODUCTION

Recently, many personal vehicles have been developed for urban use. Vehicles such as Dean Kamen's Segway, or the three-wheeled vehicle i-REAL developed by Toyota Motor Corporation[1], have demonstrated that the idea of personal motorized vehicles appeal to many people. Those machines, however, were conceived for use mainly on flat ground. Off-road applications such as forestry, agricultural activities, or inspection of electrical infrastructure in remote areas, for example, demand machines that are able to move through rough terrain. Conversely, conventional off-road machines are often excessively large, and lack the necessary maneuverability to properly carry out those tasks [2].

This paper proposes a new type of personal vehicle that was conceived for use in rough terrain applications. Its design is based on a three-wheeled configuration arranged in such a way as to allow the vehicle's driver horizontal posture to remain approximately unchanged during locomotion on rough terrain.

Fig. 1. Proposed three-wheeled body-stabilizing vehicle.

E. Ickowzcy, T. Aoki, and S. Hirose are with the Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, Tokyo, Japan `ewerton@robotics.mes.titech.ac.jp`

II. VEHICULAR SHAPES

A. Intended Applications

The most appropriate shape of a vehicle is closely related to its intended applications [3]. This research aims to develop an off-road personal vehicle for use in applications involving rough terrain locomotion at locations that could contain narrow passages and natural obstacles (e.g. trees, large rocks) around which the vehicle must maneuver. In general, activities that take place in forests and mountainous areas, for instance, present these characteristics. Such applications typically impose the following requirements: *a*) good stability and traction on rough terrain, *b*) maneuverability, *c*) reduced size, and *d*) robust and reliable mechanisms.

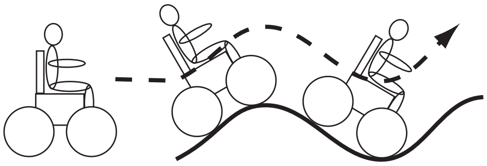
In view of those requirements, the fundamental design of such a vehicle is discussed in the remainder of this paper.

B. Number of Wheels

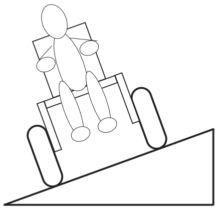
The number of wheels is one of the most important characteristics of off-road wheeled machines. Hirose *et al.* surveyed the use of wheeled rovers for planetary exploration [4]. Much of the discussion remains relevant to the development of off-road machines:

- One-wheeled and two-wheeled machines, whereas having undeniable advantages regarding simplicity of mechanism and compactness, require some special device to maintain active stability, which may hinder their applicability as off-road vehicles;
- In the case of machines with three or fewer wheels, the load can be naturally distributed among each wheel without the use of a special mechanism. Likewise, three or more wheels grant the machine the possibility of static stability. Three-wheeled vehicles thus constitute a special case in which both properties are present;
- Machines with four or more wheels can have good mobility, but in general they require more complicated mechanisms in order to properly distribute their weight, and to steer, when compared to machines with fewer wheels.

From the discussion above, machines with only one or two wheels may be problematic because they lack the feature of static stability, needing constant active stabilization to balance themselves. Vehicles with three or more wheels are statically stable and may have good off-road mobility. Nevertheless, an increase in the number of wheels of the vehicle generally results in an increase of the complexity of the mechanisms involved in its motion. In effect, some of the potential complications are:



(a) Vehicle pitching when moving through rough terrain.



(b) Vehicle's body tilts to cope with the sideways unevenness of the terrain.

Fig. 2. Example of conventional vehicles moving on rough terrain.

- Vehicles with more than three wheels may not have all their wheels contacting the ground for certain terrain geometries;
- Simple and effective steering schemes, which allow turning on the spot for example, exist for two-wheeled and three-wheeled machines. Four-wheeled vehicles usually employ either an Ackerman steering scheme, which is not capable of on-the-spot turning, or are skid-steered, which is not efficient. Efficient on-the-spot turning is technically possible for four-wheeled vehicles, but demands significantly more complicated mechanisms, such as controlling the steering angle of each wheel. Steering is frequently more complicated when the number of wheels is further increased;
- If the amount of space available for the machine is fixed, increasing the number of wheels, limits the maximum diameter of each wheel. If each wheel must, additionally, be equipped with bulky complicated mechanisms in order steer the vehicle for instance, the space occupied by each wheel is even further limited.

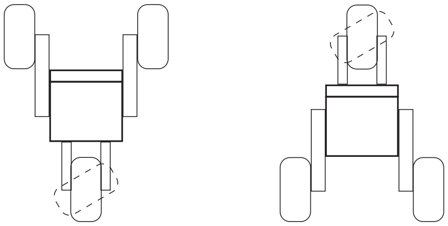
The previous considerations suggest that three-wheeled machines may be good candidates to fulfill the requirements previously presented, since the three-wheeled design provides static stability and load distribution along all wheels without the need of additional mechanisms. Additionally, steering is simplified when compared to machines with four or more wheels.

C. Body-Stabilization

When conventional vehicles move on rough terrain, the entire body of the vehicle must tilt in order to cope with the unevenness of the ground, as shown in Fig. 2. The pitching of a vehicle moving on rough terrain (see Fig. 2a) imposes several limitations to its mobility, possibly causing instability or critical vibrations[3]. Furthermore, in addition to pitching, sideways unevenness adds to the problem as well, as shown in Fig. 2b.

The concept of body-stabilization presented here is the idea of maintaining a horizontal body orientation during locomotion, thus eliminating, or at least, reducing the problems described. In order to implement it, information about the orientation of the vehicle and the terrain may be required. The vehicle orientation can be sensed by attitude sensors, which are readily available. Information about the geometry of the terrain can be acquired by laser scanners, or it can be locally estimated using on-board sensors as described in [5][6].

In the following, the design of a vehicle possessing this feature is explained.



(a) Single front wheel and two rear wheels.

(b) Single rear wheel and two front wheels.

Fig. 3. Possible configurations for three-wheeled vehicles.

III. VEHICLE DESIGN

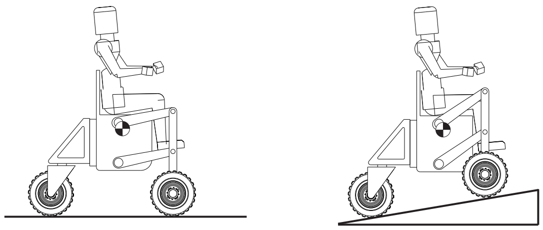
A. Initial Design Considerations

When considering the design of a three wheeled machine, two basic configurations are often used: two rear wheels with one front (possibly steerable) wheel, or one rear (possibly steerable) wheel with two front wheels, as shown in Fig. 3. When considering that a person will drive the machine, it becomes difficult to implement the former. Indeed, maintaining the body of the vehicle horizontal on rough terrain means that the wheels will have to move relative to the vehicle's body. If the single central front wheel moves, it could impair the vision of the driver. Moreover, even if the single front wheel is stationary, the machine's mechanisms and structures attaching the seat to the wheels would make boarding the vehicle from the front difficult, and the seat's backrest would prevent boarding it from the rear. With two front wheels and one single rear wheel, those problems are eliminated because the driver can be seated between the two front wheels.

B. Design with Fixed Rear Wheel

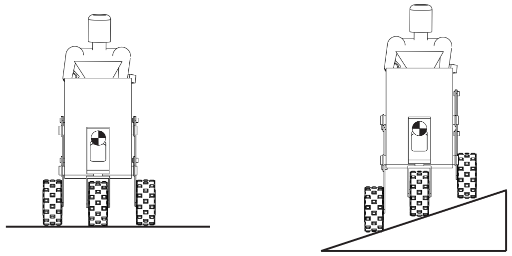
Possibly, the most intuitive representation of the ideas previous discussed may be a design in which the single rear wheel is fixed to the main body of the vehicle while the two front wheels are free to swing and adapt to the terrain, as depicted in Fig. 4. The front wheels are suspended by independently driven four-bar linkages. Those are simple mechanisms, which are robust, and can be easily attached to the vehicle's body.

The vehicle can successfully cope with slopes purely transverse (sideways) to the direction of motion, by moving its two front wheels opposite to each other while the rear wheel remains stationary. On the other hand, when faced with slopes on the longitudinal plane of motion, the range of motions of the front linkage alone is insufficient to



(a) Vehicle on flat ground (side view).

(b) Vehicle on longitudinal slope (side view).



(c) Vehicle on flat ground (back view).

(d) Vehicle on sideways slope (back view).

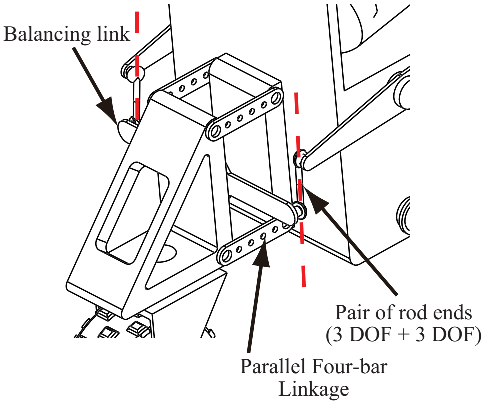
Fig. 4. Motion of a three-wheeled vehicle with fixed rear wheel, and front wheels suspended by four-bar linkages

compensate for large unevenness of the terrain (see Fig. 4b). Furthermore, the ground clearance becomes very reduced even for small longitudinal slopes. The rod-end based design is presented next in order to remedy this situation.

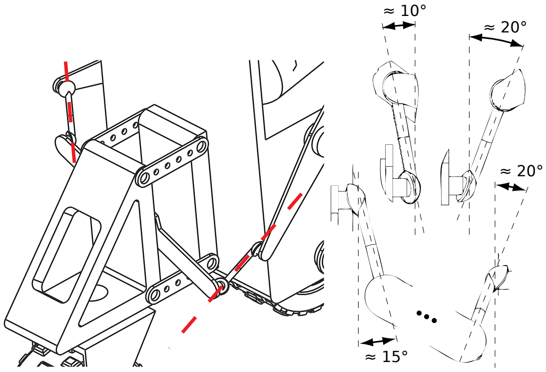
C. Rod-End Based Design

By allowing the rear wheel to move in a coordinated fashion with the front wheels, a wider range of longitudinal slopes can be compensated by the vehicle's linkage. In order to adequately connect front and rear wheels, the uppermost bar of the four-bar mechanism of each front wheel was extended to the rear, and connected to a balancing link by a pair of rod ends, in the manner shown in Fig. 5a. Notice that the rear wheel is suspended by a parallel four-bar mechanism. This parallel linkage assures that the steering axis of the rear wheel will remain vertical when the wheel moves. The motion of such a vehicle is shown in Fig. 6. Observe that when the front wheels move up, the rear wheel moves down, naturally increasing the workspace of the mechanism (see Fig. 6b). Moreover, the motion of the two front wheels is averaged by the balancing link, which defines the position the rear wheel.

There are still some problems with this design. In fact, the orientation of the rod ends varies considerably (see Fig. 5), and consequently so does the direction of the forces applied between each pair of rod ends and the other elements of the mechanism. In order to provide a more robust, but functionally equivalent design, the concept of a *sliding-rod-end* was developed and is presented next.

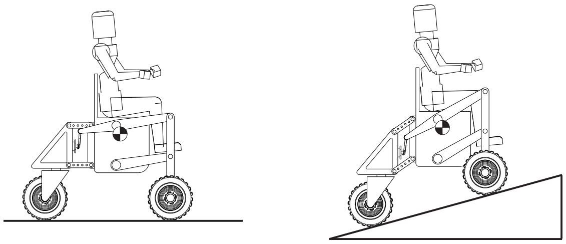


(a) Vehicle configuration on flat ground.



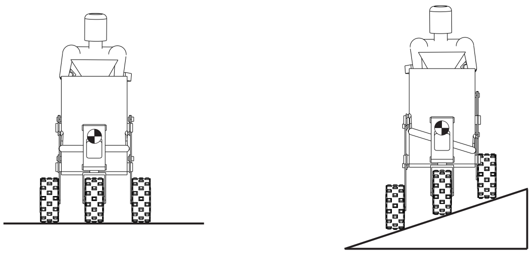
(b) Vehicle configuration on rough terrain.

Fig. 5. Connection between front wheel linkages and rear wheel supporting frame. The dashed lines represent the direction of the forces applied to/by each pair of rod ends



(a) Vehicle on flat ground (side view).

(b) Vehicle on longitudinal slope (side view).



(c) Vehicle on flat ground (back view).

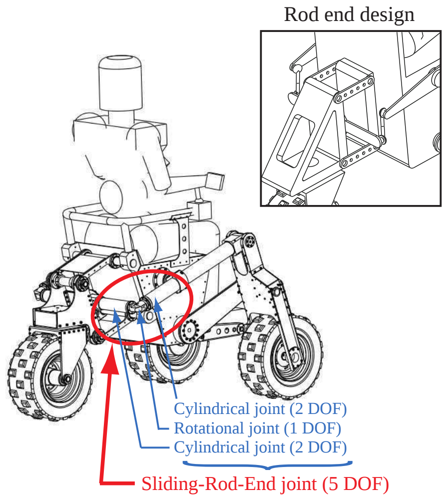
(d) Vehicle on sideways slope (back view).

Fig. 6. Motion of the rod-end based design.

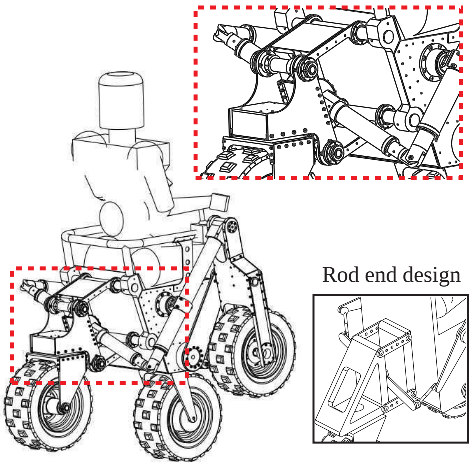
D. Sliding-Rod-End Based Design

Each rod end can be equated to a joint with three rotational degrees of freedom (DOF) (see Fig. 5a). Each side of the previously proposed vehicle uses a pair of rod ends (in principle, a total of 6 DOF) to connect the front linkage to the rear balancing link. In fact, only 5 DOF are functionally used. In effect, each side of the mechanism has an internal degree of freedom: the rotation around the common axis of the two rod ends of a pair (the dashed lines in Fig. 5), which is not harmful to the mechanism function, but is somewhat redundant. A functionally equivalent mechanism thus requires at least 5 DOF. One such mechanism, here referred to as *sliding-rod-end*, is shown in Fig. 7.

The sliding-rod-end has 5 DOF, and was constructed with two cylindrical joints (1 translational DOF and 1 rotational DOF), and one rotational joint (1 rotational DOF). The cylindrical joints were realized by using dry-bearings to slide one cylinder inside another (in dusty/dirty environments, the external cylinders can be equipped with seals for protection).



(a) Vehicle on flat ground.



(b) Vehicle on rough terrain.

Fig. 7. Replacement of the rod ends with the proposed sliding-rod-end joint.

In this configuration, apart from small frictional forces, the forces transmitted by the sliding-rod-end will always point in the radial direction of each cylinder, independently of the mechanism configuration. This situation is more robust than the previous one, when the direction of the forces acting on the rod end pairs would vary significantly with the mechanism configuration.

E. Steering

As mentioned before, the vehicle can be easily maneuvered if the single rear wheel is mounted on a steerable axis. There are three basic ways in which this could be done: *i*) using an actuator to control the steering angle, *ii*) having the axis completely free and control the speed of the front wheels, and *iii*) the same as the previous item, but equipping the axis with a brake or lock device, to block the steering axis when moving on very rough terrain.

Although the use of a steering actuator would allow a finer control of the steering process, the extra actuator would add to the total weight and complexity of the mechanism. Moreover, such fine control would be unnecessary in most cases. Options *ii*) and *iii*) are very similar, but a brake or lock mechanism is required for off-road locomotion. In effect, when moving through rough terrain, the shock between the tires and the ground could easily cause undesirable displacements in the steering angle of the rear wheel if the steering axis is not locked. When the steering axis is locked the vehicle can still perform large radius turning by skid-steering, and when more accurate maneuvering is needed, the lock can be disengaged and small radius turning (such as on-the-spot turning) can be performed as illustrated in Fig. 8.

The attachment of the lock mechanism to the rear wheel is shown in Fig. 11, and the lock mechanism's basic functioning principle is depicted in Fig. 12. When the lock mechanism is disengaged, the steering axis can rotate freely. When the steering angle approaches 0° (straight direction), the steering lock can be commanded to engage. When that happens, the spring is driven inwards, pulling the sliding pin into the locking disk's groove. At that stage, the steering is locked. Forces applied to the rear wheel that would tend to change the steering angle are transmitted from the locking disk to the sliding block to the external case. Notice that no

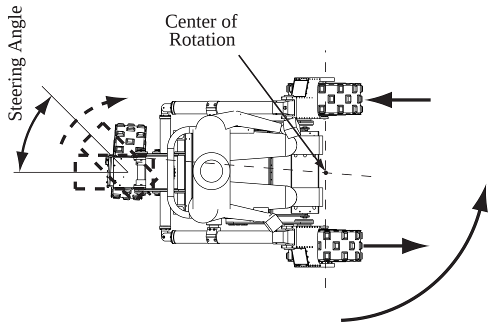


Fig. 8. Vehicle's steering mechanism, capable of on-the-spot turning.

external forces are applied to the spring. Disengaging the lock mechanism is carried out by reversing the last step (pushing the spring outwards).

Only a small actuator is needed in order to drive the spring attached to the sliding pin. Furthermore, power is consumed only while engaging/disengaging the lock. This lock mechanism was selected instead of a clutch-type brake system for simplicity. Admittedly, it could be convenient to be able to block the steering axis at any given direction, but this is unnecessary; the vehicle can generally be driven so that the steering angle will pass by the 0° position, allowing the lock mechanism to be re-engaged.

F. Front Linkage Optimization

Unlike the four-bar mechanism supporting the rear wheel, there is no particular reason, in principle, to prefer a parallel four-bar mechanism over a non-parallel design for the front wheel linkage. In order to determine the most suitable configuration for the front linkage, its parameters were chosen to maximize the stability of the vehicle on rough terrain. The concept of normalized energy stability margin [7] was used to quantify the stability of vehicles in the present paper.

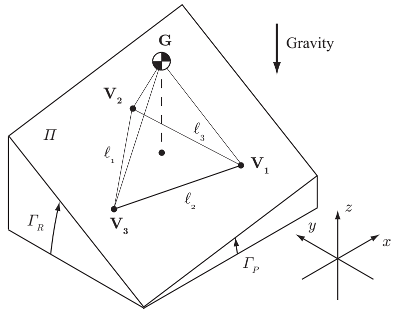
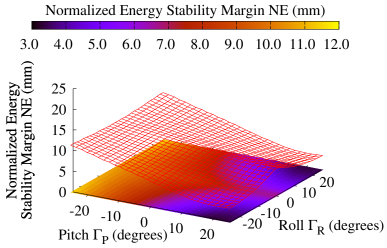
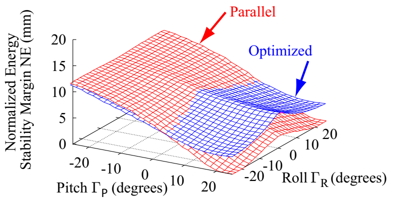


Fig. 9. Representation of a three-wheeled vehicle on rough terrain.



(a) Global NE of the vehicle with optimized front linkage.



(b) Comparison between the parallel and optimized front linkages.

Fig. 10. Stability of the vehicle with optimized front linkage.

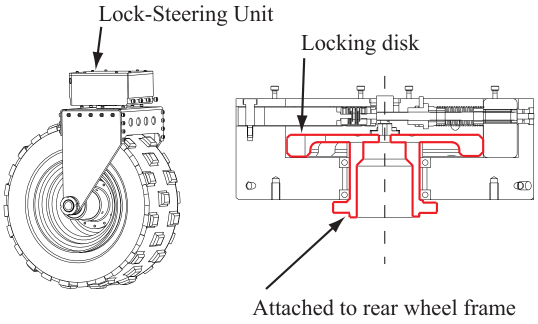
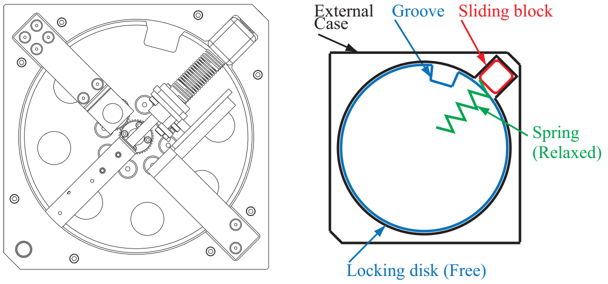
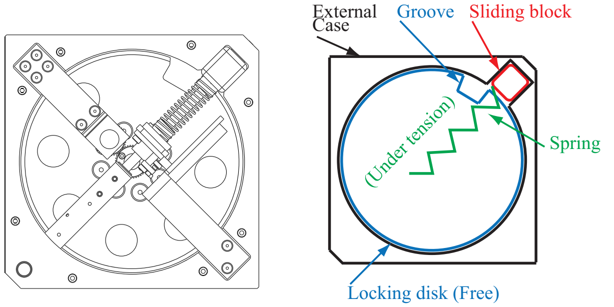


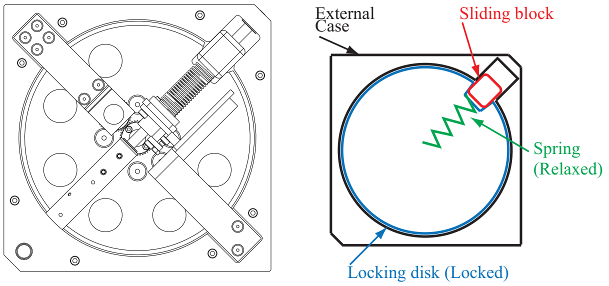
Fig. 11. Overview of the rear wheel unit.



(a) Lock disengaged, free steering. (b) Lock disengaged, free steering (simplified representation).

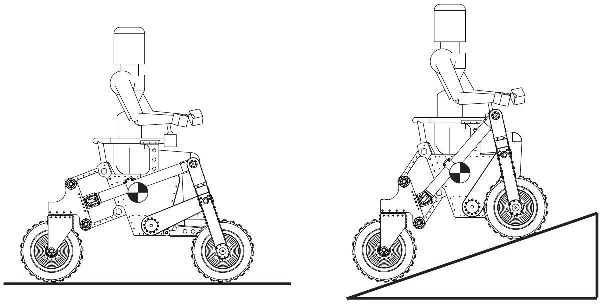


(c) Prepared to lock, spring under tension. (d) Prepared to lock, spring under tension (simplified representation).



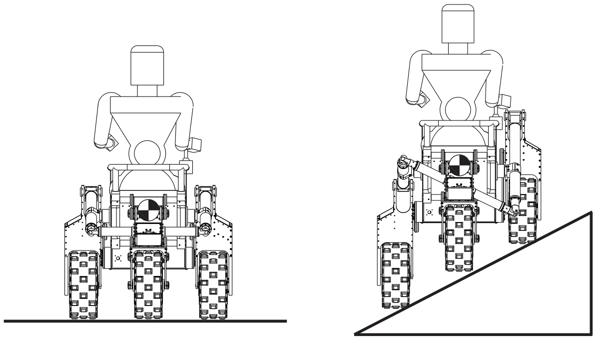
(e) Lock engaged, steering blocked. (f) Lock engaged, steering blocked (simplified representation).

Fig. 12. Functioning principle of the steering-lock mechanism.



(a) Vehicle on flat ground (side view).

(b) Vehicle on longitudinal slope (side view).



(c) Vehicle on flat ground (back view).

(d) Vehicle on sideways slope (back view).

Fig. 13. Motion of the designed vehicle.

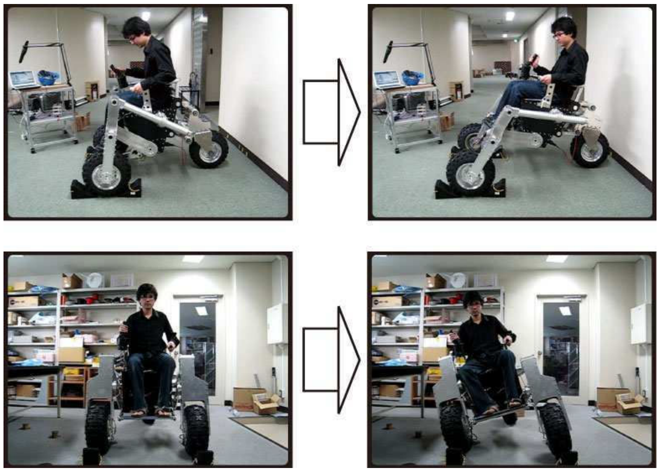


Fig. 14. Prototype test on flat ground.

TABLE I

PROTOTYPE SPECIFICATION

Geometric	
Width:	1.02 m
Wheelbase:	1.15 m
Ground Clearance:	0.30 m
Tire Width:	0.16 m
Tire Diameter:	0.40 m
Mechanical	
Mass (with batteries):	86.6 kg
Electrical	
Wheel motor:	100 W DC Brushless, Reduction: 19.32
Linkage motor:	200 W DC Brushless, Reduction: 160

The case of a three-wheeled machine on rough terrain is illustrated in Fig. 9. The normalized energy stability margin (NE) associated with the edges ℓ_n, $n = 1, 2, 3$, can be evaluated from the geometry of the problem, and the global NE of the machine is the minimum of the NE associated with each edge. The geometry of the problem depends upon the parameters of the front linkage, and thus those parameters may be chosen to maximize the NE of the vehicle. Notice that the four-bar mechanism is not ideal, from the point of view of stability (see Fig. 10b).

The motion of the designed vehicle with optimized linkage is shown in Fig. 13

IV. PROTOTYPE

A full-scale prototype of the proposed vehicle, shown in Fig. 1, was build. The prototype was constructed with a minimal number of actuators: one motor for each front wheel (the single rear wheel being passive), and two motors to control the vehicle's linkage (see table I). It has not been tested in real rough terrain yet, but basic tests were performed on flat ground to demonstrate the range of motion of the mechanism (see Fig. 14).

V. CONCLUSION

The general requirements for off-road personal vehicles have been discussed, and a new three-wheeled terrain-adaptive personal vehicle has been introduced. Furthermore, the concept of body-stabilization was explained, and a vehicle presenting such a feature was designed. The design was refined in order to produce a practical machine which is compact, maneuverable, robust, and does not rely on overly complicated mechanisms.

REFERENCES

[1] Toyota personal mobility website. [Online]. Available: http://www2.toyota.co.jp/en/tech/p_mobility/i-real/

[2] S. Hirose, K. Kuramitsu, Y. Ota, and T. Aoki, "Development of FALCON, a three wheeled personal vehicle for uneven terrain," in *Proc. of Safety, Security and Rescue Robotics*, 2006.

[3] M. G. Bekker, *Theory of Land Locomotion: the mechanics of vehicle mobility*. The University of Michigan, 1956.

[4] S. Hirose, N. Ootsuka, T. Shirasu, H. Kuwahara, and K. Yoneda, "Fundamental considerations for the design of a planetary rover," in *Proc. IEEE International Conference on Robotics and Automation*, May 1995.

[5] K. Iagnemma, A. Rzepniewski, and S. Dubowsky. (2003) Control of robotic vehicles with actively articulated suspensions in rough terrain. [Online]. Available: http://robots.mit.edu/people/Karl/Aut_Robots_2003.pdf

[6] K. Iagnemma and S. Dubowsky, *Mobile Robots in Rough Terrain*, B. Siciliano, O. Khatib, and F. Groen, Eds. Springer, 2004.

[7] S. Hirose, N. Ootsuka, T. Shirasu, H. Kuwahara, and K. Yoneda, "Normalized energy stability margin: Generalized stability criterion for walking vehicles," in *Proc. Int. Symp. on Climbing and Walking Robots (CLAWAR)*, Brussels, Belgium, Nov. 1998.