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Full paper

Development of tethered autonomous mobile robot systems for field works

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Abstract—This paper describes the implementation details, advantages and potential applications of autonomous tethered mobile robot systems using the 'hyper-tether' concept. Hyper-tether is a new research area on tethered connections, which provide tethering among different mobile robot types, such as a robot with the environment and a robot with humans and animals. Its basic function is to actively control the tether's tension and/or length, but it also considers tether launching, anchoring, power delivery, data communication cabling and built-in trajectory command generation capabilities. Many of these features can be efficiently applied to build a tethered mobile robot system which remotely manipulates a working tool that can be useful for land-mine detection and removal, trimming of gardens and grass cutting of wide areas (e.g. golf courses, soccer and baseball fields), spraying of agricultural chemicals, forestry and construction works, etc. In this paper, a simple prototype of hyper-tether's winch-tether pair and a working tool equipped with a grass cutter was constructed, and basic experiments were performed to demonstrate the validity of the proposed system.

Keywords: Hyper-tether; winch; grass cutting; mine detection and removal.

1. INTRODUCTION

Tethers have been used for a long time in many areas, including ground, underwater and aerospace environments. For these applications, a tether configuration can be as simple as a rope or chain for tethering animals, and as sophisticated as cabling for underwater submersibles which provides air, power and communication links with the surface. In robotics, the phrase tethered robot system generally has been used for describing mobile robots restricted by power supply and/or data communication

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cabling. On the other hand, the word ‘untethered' has been mostly used to emphasize autonomous mobile robots with an on-board controller and power source.

A winch system for reeling in/out the tether is a fundamental tool for many practical real-world applications. Adding electric power transmission and data communication capabilities through a high-strength tether further enlarges the areas in which tethered systems can be efficiently applied. Although the use of a high-strength electrical tether is not an entirely new concept, its use in robotics has not been widely considered. For these reasons, the authors have been proposing a new area of research called ‘hyper-tether' [1–4], which includes advanced features such as automatic follow the leader command generation, tether launching/throwing, and anchoring to trees and rocks. Hyper-tether also features a cable communication network and energy distribution optimization.

We first introduce the hyper-tether concept, its basic hardware and potential applications. Then the new concept of a tethered mobile robot system and a far-reaching tethered working tool is introduced. Next, details of a winch, tether and working tool prototypes are explained. Finally, some experimental results are presented, which show the validity of the proposed systems.

1.1. Previous work

Tethers have been used for helping robot locomotion on steep slopes, as can be seen in Dante II [5] and TITAN-VII [6] applications. In both cases tethers were stacked in electric winches, and their lengths and/or tensions were controlled. Moreover, Dante II's tether also included power and data transmission conductors. Some other recent studies on cable crane robots [7–9], autonomous cable winding and pay-out [10], space robots [11, 12], rope interfaces [13], casting manipulators [14], cable-driven robots [15–17], and path planning [18] also used tethers to some extent.

2. HYPER-TETHER

2.1. Concept

Hyper-tether is a new research area where systematic investigations on tethered connection applications is considered [4]. This research includes, but is not limited to, the following features:

(i) Connection among different mobile robot types, robots with the environment, and robots with humans and animals.
(ii) Multiple connections among these parts.
(iii) Mobile robots locomotion assistance and cooperative control.
(iv) Power delivery and data communication.
(v) Tether's length and/or tension control.

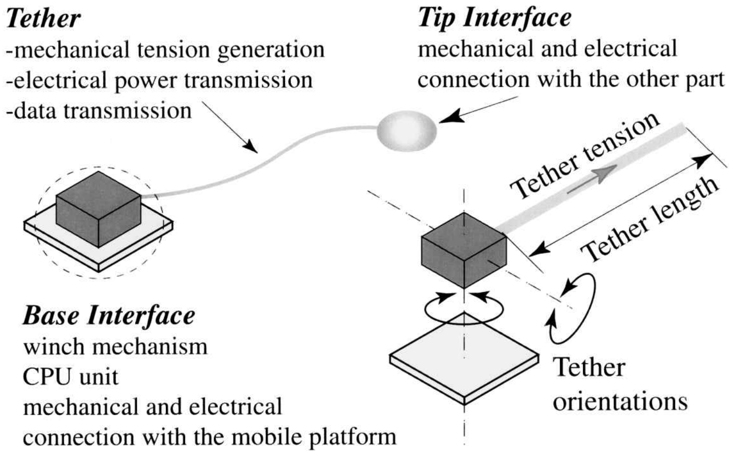


Figure 1. Hyper-tether basic hardware.

(vi) Tether throwing/launching.
(vii) Tether anchoring to the environment.
(viii) Trajectory generation to follow the tether tip.

A basic device as shown in Fig. 1 and called ‘hyper-tether basic hardware' extends the capabilities of the traditional winch/tether pair and forms the fundamental part of this research. Its details are explained next.

2.2. Basic hardware

The basic hardware of a hyper-tether system consists of a tip interface, a tether and a base interface. These parts are implemented with one or more of the following characteristics and functions:

(i) *Tip interface*: simple mechanical and electrical connection with the other part; tether thrusting device; anchoring capability on rocks and/or trees.
(ii) *Tether*: small outer diameter; lightweight; high strength; good flexibility; abrasion resistant; high power transmission with good efficiency (low wire resistance); high data communication bandwidth; bidirectional transmission of power and data.
(iii) *Base interface*: fast reel in/out; high-torque reel in/out; tether's length, tension and orientation sensors; mechanical connection with the mobile platform; power line and data communication connection with the mobile platform; tether launching/throwing device.

2.3. Advanced features

Hyper-tether research also considers the autonomous ‘follow the leader' type of locomotion, the power line cable communications network and power distribution optimization, which are explained below.

(i) *Autonomous 'follow the leader' type locomotion.* Tracking of the tether tip position relative to the base interface can be accomplished by monitoring the tether's length and orientation. If the mobile robot on which the base interface is mounted can track it's own position/orientation relative to a inertial reference frame, say $\sum_g$, the tether tip's trajectory history can also be known relative to the same $\sum_g$. For such a condition, it is straightforward to derive a follow the leader-type trajectory tracking algorithm, which makes the tether base trajectory asymptotically approach the tether tip trajectory [2].

(ii) *Power line cable communications network.* Wireless communication technology has become very important for building 'untethered' mobile robot systems, because tethers degrade mobility. However, as hyper-tether systems are connected by tethers, very reliable cable communication links can be established at no extra cost. Furthermore, using power line communication technology where data transmission and power delivery are accomplished on the same pair of electric conductors, the number of electric cables inside the tether can be minimized.

(iii) *Power distribution optimization.* Although recent advances in chemical battery technology have greatly improved their power/weight ratio, the total weight increase required to store enough energy for long-term continuous operation is still a prohibitive payload for most mobile robots. However, for a hyper-tether system, the electrical power source consisting of batteries or generators using fossil fuel engines can be carried on a crawler or wheeled platform that offers high payload capacity. The electricity can then be delivered to other mobile robots such as walking robots using the tether's built-in conductors. This power distribution scheme greatly improves the total time of continuous operation for the entire mobile robot group.

2.4. Potential applications

The hyper-tether concept can be advantageously applied to many traditional and new applications.

(i) *Cooperative material transportation.* A system of load transportation as shown in Fig. 2 can be considered, which combines walking machines mobility and crawler or wheeled robots payload capability advantages. In this scheme, the walking machine stands on the top part of the hill and, after fixing firmly to the ground, pulls the crawler upward. The 'follow the leader' locomotion, cable communication and power distribution optimization described above can be efficiently implemented.

(ii) *Stable locomotion on steep slopes.* Hyper-tether hardware can become useful for assisting robots or humans moving on steep slopes, as shown in Fig. 3. Note that hyper-tether applications are basically realized by mounting the base interface on the mobile platform instead of fixing it on the ground. This method greatly reduces the friction between the tether and the environment because the tether reel in/out can be synchronized with the mobile platform motion.

(iii) *Locomotion of micro-rovers in a micro-gravity environment.* Sample return and engineering test missions to small asteroids are being planned by several agencies (http://www.muses-c.isas.ac.jp/), and micro-rovers to move over these minor bodies and execute engineering test missions are been considered. However, because the small gravitational acceleration of about 1/100 000 compared to Earth, in such an environment any wheeled, walking or hopping mobile robot's moving velocity should be limited to about 10 cm/s in order to avoid escaping from the object's surface. The authors proposed some methods

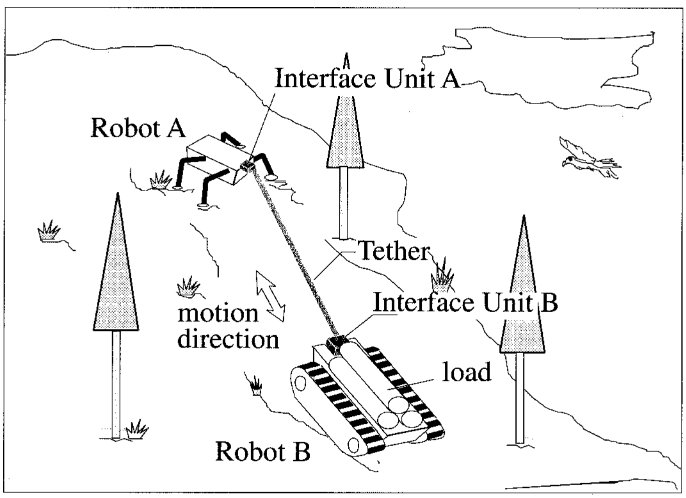


Figure 2. Cooperative motion between different mobile robot configurations.

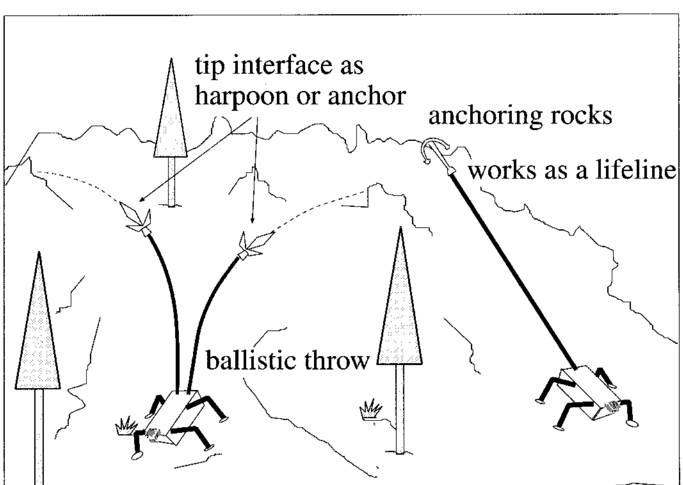


Figure 3. Harpooning and anchoring rocks to climb up and down steep terrain.

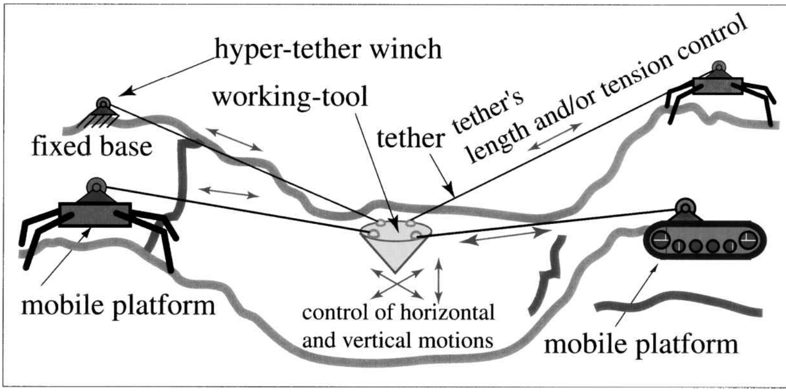


Figure 4. Basic concept of the far-reaching tethered working tool.

for fixing the rover to the asteroid or coiling around the entire asteroid using the hyper-tether concept [3].

(iv) *Far-reaching tethered working tool.* Cable suspended manipulators present good characteristics such as large workspace, good reconfigurability/adaptability and fast and simple installation, low weight, good energy efficiency, and the fact that coordinates for operation and control can be defined in place [7]. Additional research on wire/cable-driven parallel manipulators are available in the literature [7, 9, 15, 17], but from the author's knowledge none of them have considered mobile platforms to move the winch bases while performing tasks. In this research, we consider such a condition as shown in Fig. 4, where the hyper-tether basic hardware's base interface can also be set on a mobile platform, so that it can move instead of just being fixed, as in the former works. This approach that we call 'far-reaching tethered working tool', can take advantage of most of the characteristics of cable suspended manipulators. Furthermore, it extends the working space to an almost unlimited area, reachable by the mobile platform.

3. TETHERED AUTONOMOUS MOBILE ROBOT SYSTEMS FOR FIELD WORKS

The far-reaching tethered working tool can be configured as an autonomous intelligent system and its advanced properties are of interest in the research of 'super mechano-systems'. Moreover, practical and useful applications in the real world can be implemented by a minimized far-reaching tethered working tool system configuration that uses only two mobile platforms as shown in the examples illustrated in Figs 5–7. This system can be used to realize practical autonomous tethered mobile robot systems for field works. Some of these applications are listed below.

- Weed removal (Fig. 5).

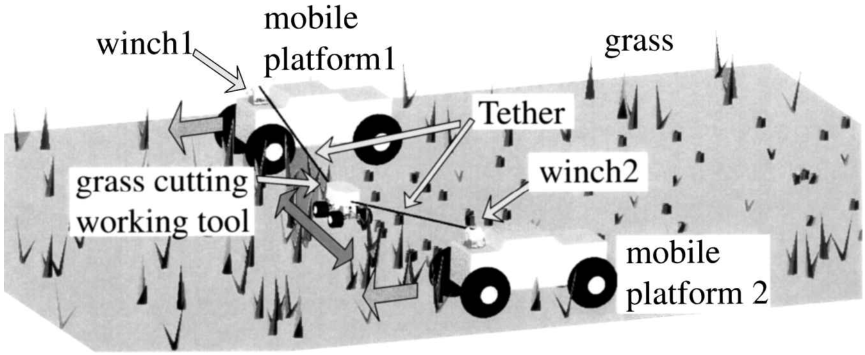


Figure 5. Example of a two-point moving working tool.

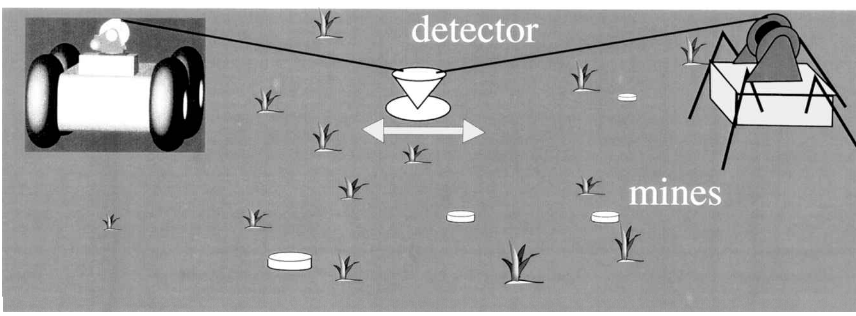


Figure 6. Mine detection and removal.

- Trimming of gardens and grass cutting of wide areas, such as golf courses, soccer and baseball fields.
- Mine detection and removal (Fig. 6).
- Spraying of agricultural chemicals (Fig. 7).
- Conveyance of goods in mountainous areas.
- Forestry and construction works.

Note that although many applications take advantage of having the working tool suspended in the air, the tension of the tethers will be very large when the system is operated on the plane, because the angles between the tethers and the working tool become very small. However, the use of working tool suspended in the air is considered as an advantageous feature, not a constraint. This research also considers applications where it is convenient to have the working tool on the ground. In such situations, wheels or free casters can be used to partially or totally support the working tool weight, greatly reducing the energy consumption of the overall system.

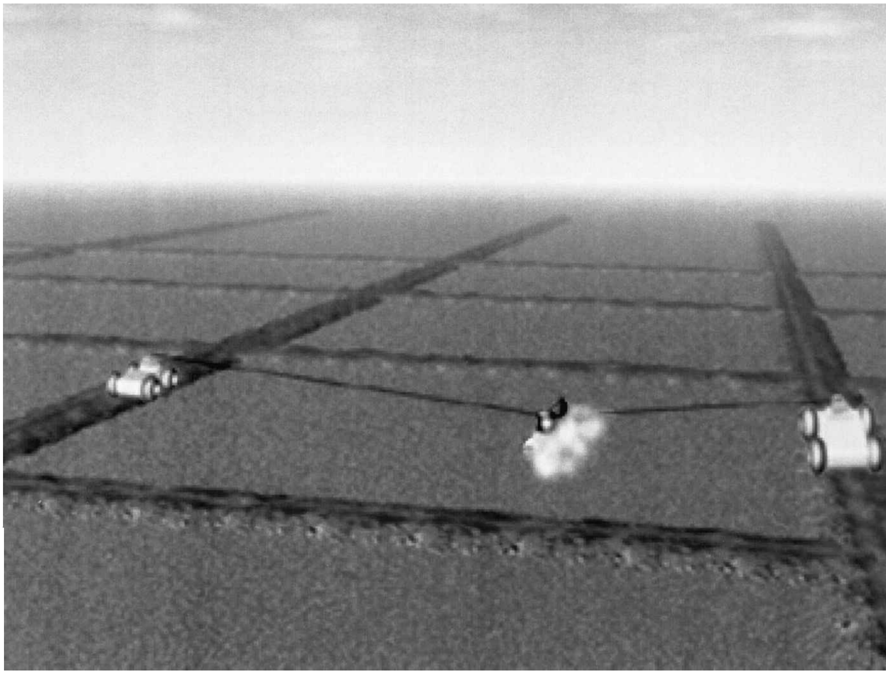


Figure 7. Spraying of agricultural chemicals.

3.1. Position control

The basic control scheme for the proposed two-point system consists of two motion steps: (i) a fast lateral motion of the working tool between the two mobile platforms, and (ii) a slow and intermittent forward motion of the mobile platforms. In the first step, the mobile platforms stand still while the working tool position is controlled by changing the tethers lengths. In the next step the mobile platforms are moved forward to the next stand point. Of course, in order to enable full area coverage the forward motion distance must be less or equal to the width that the working tool can cover in one motion step.

Motion control of mobile platforms depends on the type of platform, i.e. a walking robot or a wheeled mobile robot, etc. and their studies are out of the scope of this paper. On the other hand, position control of the working tool is easily accomplished by controlling the length of the tethers connected to both sides of the working tool. Formulation of position control can be done in either absolute or relative coordinates. Although both formulations are straightforward, in this paper an example of formulation using relative coordinates is described below. Nonetheless, for real applications, odometry and global positioning system (GPS) technology can be used for estimation of the mobile platform's absolute positions, and position control using absolute coordinates can also be used for real applications.

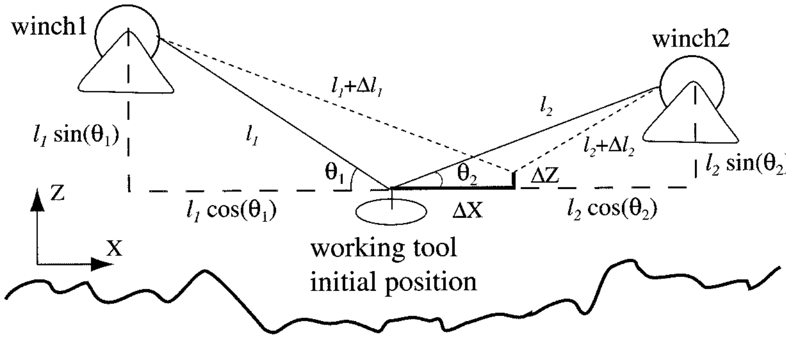


Figure 8. Working-tool relative position control. ΔX, ΔZ: working tool desired displacement (input); l_1, l_2: tether length (measured); θ_1, θ_2: tether orientation (measured); Δl_1, Δl_2: tether additional displacement (calculated).

3.1.1. Position control using relative coordinates. A basic configuration and the variables for the position control using relative coordinates is shown in Fig. 8. The control inputs are given by the desired relative lateral and vertical displacements ΔX and ΔZ, with reference to the actual working tool position. From the measurements of the initial tether lengths l_1 and l_2, and the angles θ_1 and θ_2, it is straightforward to derive the following equations that calculate the new tether lengths considering the additional displacements Δl_1 and Δl_2:

$$l_1 + \Delta l_1 = \sqrt{\{l_1 \sin(\theta_1) - \Delta Z\}^2 + \{l_1 \cos(\theta_1) + \Delta X\}^2}, \tag{1}$$

$$l_2 + \Delta l_2 = \sqrt{\{l_2 \sin(\theta_2) - \Delta Z\}^2 + \{l_2 \cos(\theta_2) - \Delta X\}^2}. \tag{2}$$

Note that the angles θ_1 and θ_2 can be either measured by the connecting interface mounted on the working tool or by the hyper-tether base interface. The tether lengths are measured by the winches.

4. DESIGN ISSUES AND PROTOTYPES

In this section, the construction details of our first tether, winch and working tool prototypes are described.

4.1. Tether prototype

Most hyper-tether applications need to bear heavy tensile loads while conducting electricity at the same time. As high tensile strength electrical conductor material is not available at present, a layer of strengthening material which bears almost all the tether tensile load is added for such a purpose. Useful references concerning this kind of tethers with electrical conductors and strength members are available in

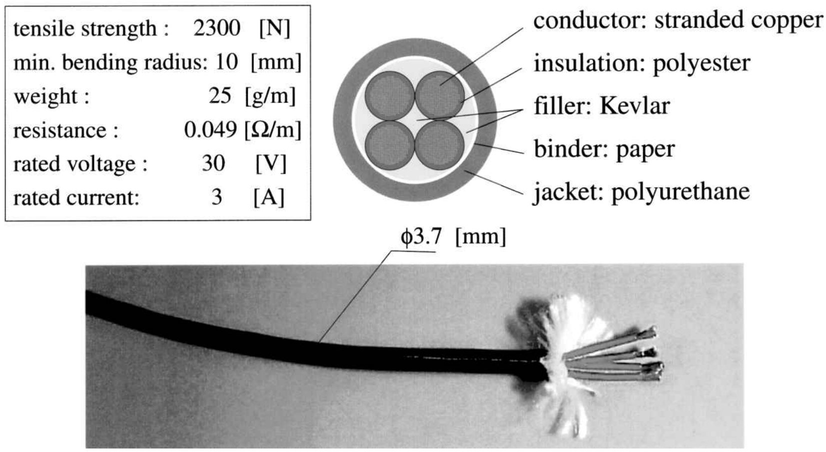


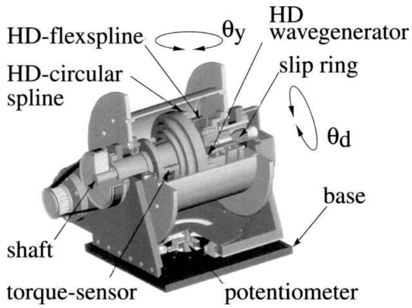
Figure 9. Tether construction and specifications.

space tethers [12] and in Dante-II's research [6] literature. Many innovative lightweight/high-strength fibers such as Kevlar (Dupont), Technora (Teijin), Dyneema (Toyobo), PBO [poly(p-phenylene-2,6-benzobisoxazole)] fiber 'Zylon' (Toyobo) and their variants are used in sails, mountain climbing ropes, nets, clothes, and also as tension member for slings and optical fibers. Differences in flexibility, tensile and fatigue strength, density, impact strength, durability, and creep (elongation that results from a load applied to the fiber for an extended period of time) characteristics should be considered for choosing the ideal filler material for constructing the tether.

One of the goals of this research is to develop high-strength tethers suitable for each application listed above. Although a proprietary tether design is not being sought yet, a custom-made tether prototype was already developed in conjunction with a cable company. The mechanical and electrical characteristics, and the construction details are shown in Fig. 9. For reasons of availability and process facilities, Kevlar was used as the filler material. Two pairs of copper conductors, one for power and one for data transmission, were considered in this first design. However, as high bandwidth power line data communication becomes available, future designs will have only one pair of conductors, so that slip-rings and electrical connections can be simplified.

4.2. Winch prototype

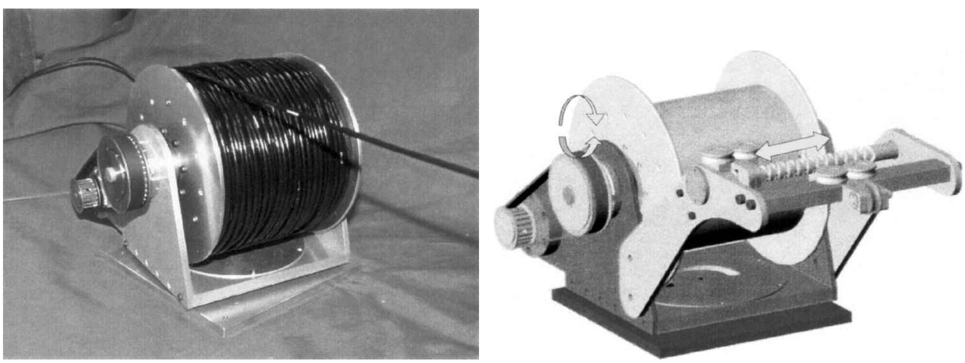
The hyper-tether base interface consists of a winch mechanism, mechanical and electrical interfaces to the mobile platform, and tether launching/throwing devices. A first simplified prototype without launching/throwing capabilities is shown in Fig. 10a and b, which is equipped with a two-channel slip-ring, a torque sensor, and potentiometers for tether length and orientation measurements. In this prototype, unexpected θ_y rotations of the winch around the base can occur. Two possible solutions can be considered: (i) adding a guide to constrain the force vector from



Specifications

Tether length	30	[m]
Rated velocity	0.3	[m/s]
Rated force	1000	[N]
Slip ring spec.	500V/4A	
Power transmission	30V/3A	
Dimensions(WHL)[mm]	150x190x200	
Weight	4.0	[kg]

(a)



(b) (c)

Figure 10. Base interface with winch specification. (a) Winch details. (b) Actual winch. (c) A level-winder mechanism for future design.

the tether to always pass through the θ_y axis and (ii) actively controlling the θ_y angle, instead of letting it rotate freely. Moreover, problems of slack tethers and knifing as described in [5] are mostly likely to occur when the winch is actuated in many different working modes. For these reasons, introduction of levelwind and pre-tensioning mechanism as shown in Fig. 10c are also being considered for improving the hyper-tether basic hardware.

4.3. Tip interface

The tip interface provides mechanical and electrical connection with the other parts. A simple coaxial connector should be effective for this purpose, but as it has to support high-tensile force, an optimal way to accomplish this is still under investigation. The tether tip can be connected to the other robot, or with the far-reaching working tool, and also be equipped with a thrusting device to assist in reaching far distant points that cannot be covered by the ballistic launching/throwing device at the base interface. Thrusting devices can be electric or gas-powered fan motors, explosive charges, rocket fuel engines, polyethylene terephthalate resin (PET) bottle rockets, etc. Furthermore, anchoring mechanisms for fixing the tip to a tree or on rocks are also under investigation.

4.4. A wheeled working tool equipped with a grass cutter

As explained above, there are applications where it is convenient to have the working tool running on the ground. Grass cutting of wide areas and mine detection are some examples. At first, it seems strange to consider mine detection; however, it is known that mines in general are set to detonate at pressures exerted by humans, so that small animals or even lightweight mobile robots are safe to move on the mine fields. Although the far-reaching tethered working tool can be made light, there are explicit advantages for using wheels. One is the decrease of energy consumption, because the working tool weight can be supported on the ground instead by the tethers and winches. Another advantage is the increase of stability. For working tools suspended in the air, oscillation can occur due to winds and other external forces.

For these reasons, a working tool as shown in Fig. 11 was considered in our first prototype. This mechanism features front and rear independent steering and active wheels, on-board computers and batteries, and it can move autonomously without the tethers. This was considered in order to have a working tool that can move from one mobile platform to another and establish the tether connections autonomously. Nonetheless, the on-board battery capacity is limited for weight reasons and the working tool can operate autonomounsly just for a short time. In the normal operation mode, hyper-tether's power delivery capability is used for operating the grass cutter for a long uninterrupted period of time.

As mentioned above, the tip interface of the hyper-tether basic hardware was not implemented. For this reason, a customized attachment was designed for the working tool prototype. In the future designs, a general tip interface that can be easily attached and detached to the working tool is to be considered.

Specifications

Dimensions(WHL):	400 x 340 x 580	[mm]
Weight:	7.8	[kg]
Rated voltage (battery):	12	[V]
Rated capacity (20 hours):	1.2	[Ah]
Cutter diameter:	160	[mm]
Steer angle:	20	[degree]
On-board PC:	Pentium-233MHz,PC/AT	
Steering mode:	front and rear independent	
Drive mode:	4 wheels drive(differential)	
Sensors :	tether's tension tether's orientation	

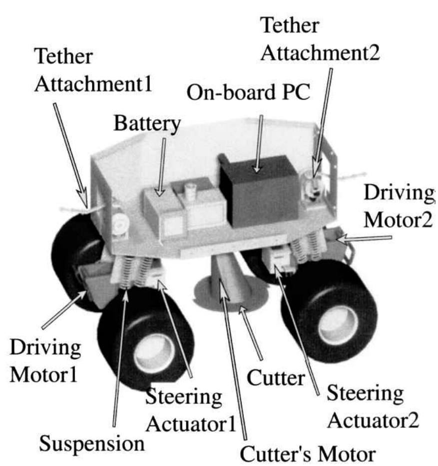
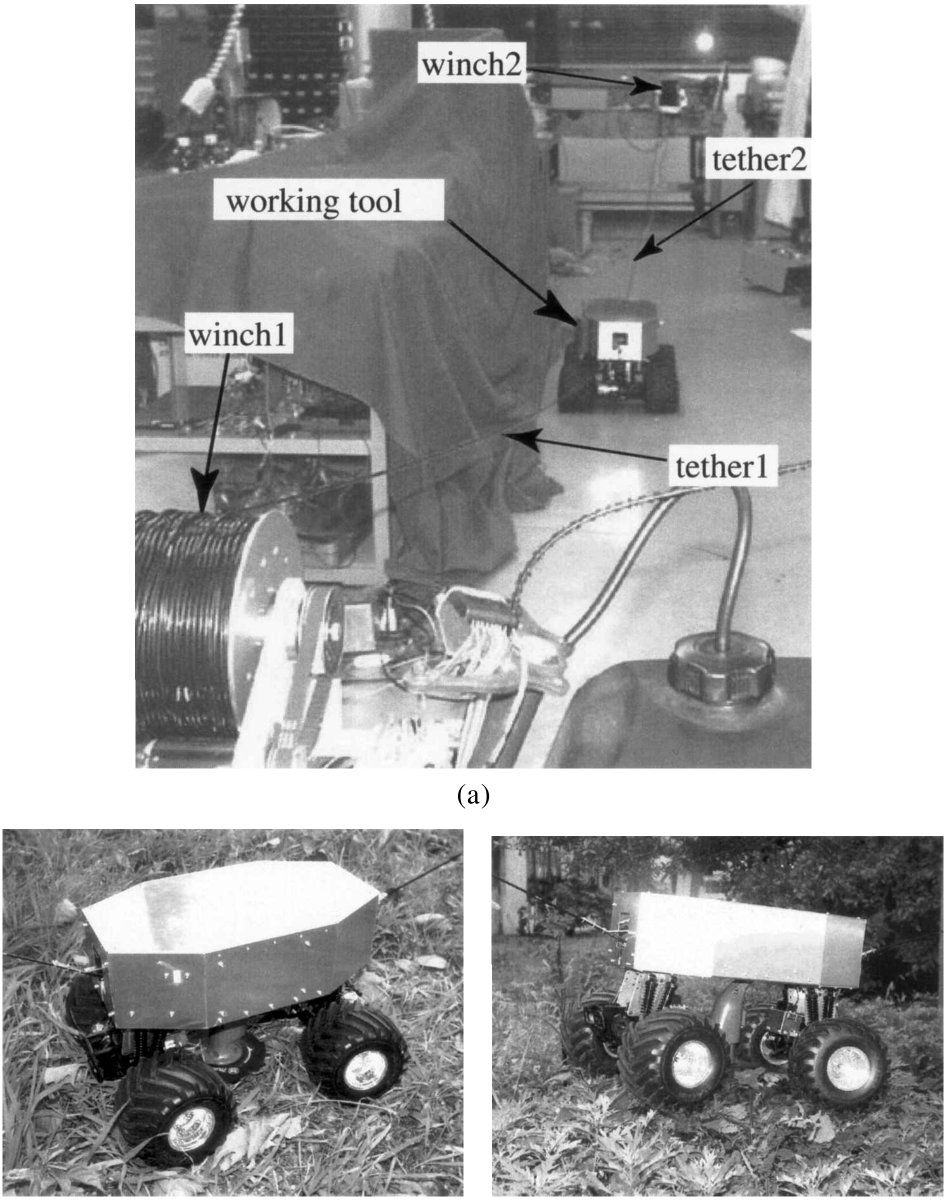


Figure 11. A wheeled working tool equipped with a grass cutter.

5. EXPERIMENTS

Some indoor experiments using the developed prototypes were done in performed to verify the validity of the proposed system. The indoor experiment set-up is



(a)

(b) (c)

Figure 12. Overview of position control and grass-cutting experiments. (a) Working tool position control with tether length and wheel torque control. Grass-cutting experiment (without winch action): (b) on the ground and (c) suspended in the air.

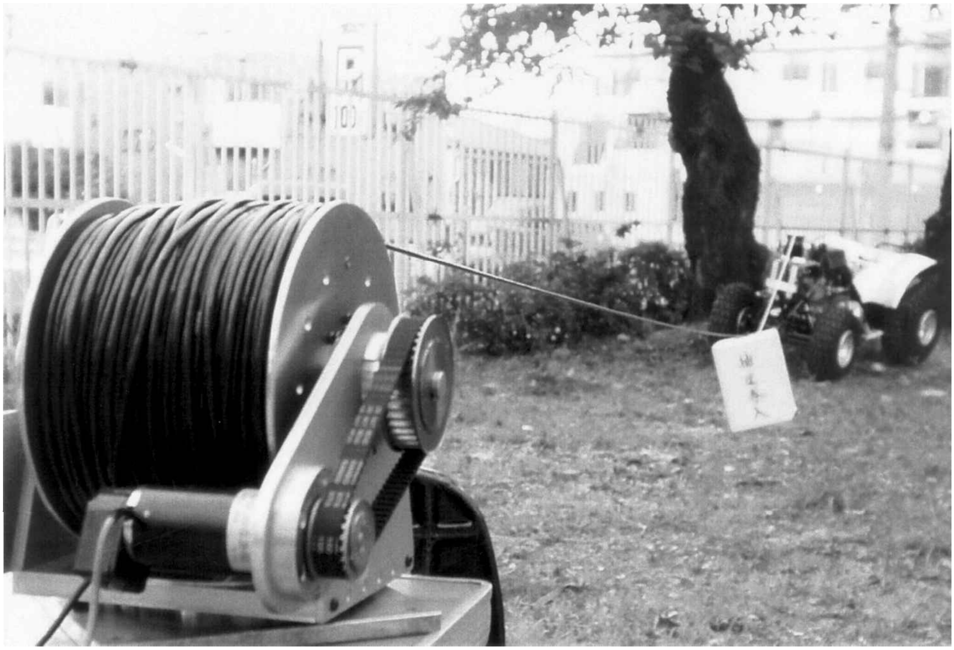


Figure 13. Overview of an outdoor experiment (with a dummy working tool).

shown in Fig. 12a and a grass-cutting experiment overview is shown in Fig. 12b. In this basic experiment, two winches with the above-introduced tether were used — one mounted on top of a mobile platform and the other fixed to a solid base. The θ_y angular motion freedom was constrained to not move on each winch and the working tool was moved between a span of about 9 m. For this experiments the position control was successfully performed by the equations (1) and (2).

Outdoor experiments are programmed to be performed as soon as we finish the development of a mobile platform with an electricity generation capability. This will be accomplished by converting a commercial four-wheeled buggy equipped with a fossil fuel engine and an alternator to generate electricity. This buggy will be used as one of the mobile platforms as shown in Fig. 13. The other mobile platform can be an electric-actuated crawler-type or quadruped mobile robot. Details of the conversion and results of the outdoor experiments will be reported in future work.

6. SUMMARY AND CONCLUSIONS

The basic concepts and design issues for the tether, winch and other fundamental elements of the proposed hyper-tether research were introduced and explained in detail. Advantages and examples of potential applications were also introduced. Among them, the far-reaching tethered working tool concept was further explored, and a minimized system that uses only two mobile platforms and can be used in many real-world applications was the main topic of the rest of the paper.

A tether, a winch and a wheeled working tool prototype were built, and the validity of the proposed system was verified by basic experiments. There are still many improvements to be done on the hyper-tether basic hardware, but this research aims to provide a general and multi-purpose hyper-tether basic device as soon as possible. Moreover, many other kinds of working tools are planned to be built and tested in real field works.

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