Recent Advances and Applications of Tethered Robotic Systems

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RECENT ADVANCES AND APPLICATIONS OF TETHERED ROBOTIC SYSTEMS

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ABSTRACT — With the advancement in technology, the field of robotics has evolved differently in multiple domains. For use in industries huge and autonomous robotic systems are developed. On the other hand, the increased demand of robotics in rescues, space and warfare has urged the development of compact and sophisticated systems. That's where the concept of tethered robot arises. Several advantages of tethered system are realized: a) robot size decreases significantly b) enables it to maneuver in narrow spaces c) have a continuous power supply d) provides reliable communication link. This paper presents state-of-the-art comprehensive review of tethered systems and associated challenges. This research work is anticipated to assist researchers in developing the advanced tethered robots by doing the analysis of existing systems.

I. INTRODUCTION

Robotics is a combination of various disciplines such as electrical and electronics, computer science and engineering, mechatronics and mechanical design, control and automation systems. Progress in the field of science and technology has emerged new, innovative and interesting fields. The domain of robotics is an example of one of such fields. History of robotics dates back to 1920s. However, the last two decades witnessed technological as well as social revolution in this domain widening the spectrum of robot applications dramatically. Today, robots are being used actively in rehabilitation [1-5], motion assistance [6-9], cognition [10, 11], haptics/VR [12] and target detection and tracking [13, 14] in addition to Nuclear Power Plants (NPP) [15], Space [16, 17] and numerous other industrial applications [18-20].

A leash that anchors something such as animal, is called tether. Accessing the Internet through a cellular phone via Bluetooth or data cable is also sometimes termed as tethering. Tether can be a sophisticated physical link in form of cable for underwater submersibles. Such tether provides link for communication, air source and power supply from the surface. In robotics, mobile robots having cable connection for data communication and/or power supply are termed as tethered robots [21]. On the other hand, untethered robots are the autonomous mobile robots which have onboard power source and controllers. Winch is the fundamental part of tethered system in many practical applications. Other parts of tethering system include the components that carry out the reeling and stack of the tether [22]. Along with the provision of the physical support, tether can also be used as a mean to communicate data between remote control unit and tethered system. Tether can be utilized as a medium to supply oxygen and hydraulic fluids from surface ship to submersibles. Similarly, material from a vacuuming robot can be transported easily to the surface through a tether. For a long time, tethers have been extensively used in various areas including under-water, ground and aero-space environments.

Mobile robotic platforms have large mobility within their working environment. Such robots have large area of applications including medical, agriculture, military, industry and space exploration. Over the last few years, mobile robot systems have demonstrated the ability to operate in constrained and hazardous environment and perform many difficult tasks. Many of these tasks demand tethered robot systems. Tether provides the locomotion and navigation so that robot can move on steep slopes. Use of tether in cable crane robots, casting manipulators, space robots, robot path planning and autonomous cable winding and unwinding have also been reported. This article is dedicated to literature survey of different applications using tether. Tethered robotics for rescue operations, in underwater systems, in space and other terrestrial applications have been discussed.

The rest of the paper is structured as follows: Section II presents rescue robots while underwater robotics has been discussed in Section III. Section IV highlights tethered systems for space exploration. Other terrestrial tethered robotic applications are presented in Section V. Finally Section VI comments on conclusion.

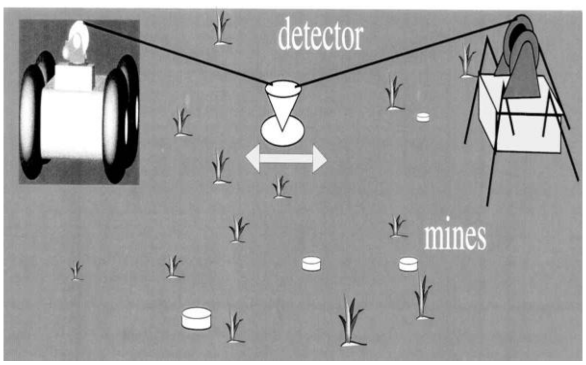
II. RESCUE ROBOTICS

One of the major advantages of mobile robots is their ability of operation in unreachable environments. These robots can work in hazardous places where human lives could be at risk. Urban search and rescue is one of the most challenging situations conceivable. In result of natural disasters, victims are often found in unreachable locations and mostly buried under wreckage of collapsed buildings. The robots that have been specifically designed for searching and rescuing purposes lie in the domain of rescue robotics. The rescue robots extend the capabilities and safety of human rescuers.

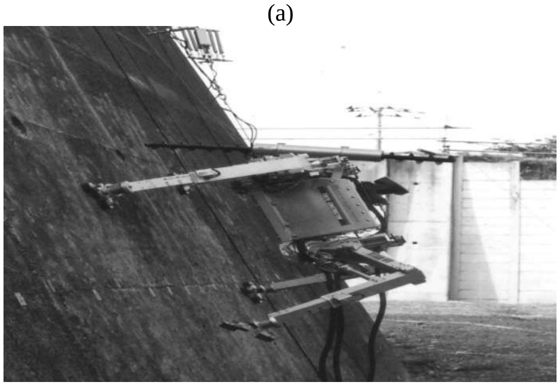
On Sept. 11, 2001, such robots were used at world trade center disaster to rescue thousands of survivors. Tethered robots with radio communication based controller were deployed eight times in the helter-skelter environment of the demolished towers. During the operation the robots faced a number of complications involving tether management**,** poor maneuverability and radio transmission inefficiency [23]. The problem of using radio frequencies at tragedy sites has been raised in these rescue operations. It became evident when temporary loss of an untethered tele-operated robot happened due to communication failure. Communication with robot has to be managed in small range of frequencies as most frequency bands are reserved by emergency response agencies. Additionally, radio communication signals are often blocked by the dense wreckage. These issues demand more useful and reliable point to point navigation of robots that can only possible with tethered system. Tethered robots can be moved safely in upwards and downwards directions whereas vertical motion of untethered robots is not an easy job. On the other hand, tether can increase the chance to catch on obstacles.

A tether design is required that actively solves or prevents entanglement problems so that it provides more range and mobility for the rescue robots at competitively low price. Perrin *et al*. proposed a novel actuated tether design for rescue robots using hydraulic transients [24]. For this design, the motion along the tether is created by arresting the flow of water in the tether. By inducing movement along the tether it can be freed if caught. The chance to get caught in the start is eradicated by such kind of motion.

Figure 1 shows application of tether in safety and rescue robotics. Further advancements in rescue mobile robots, specially based on hyper-tether concept, are anticipated [25]. In hyper-tether system, the strong and high-strength tether is used with built-in electrical conductor. The prominent feature of such scheme is the use of onboard winch or reel to reel-in or reel-out the tether. The reeling is synchronized with the motion of mobile robot. In this concept, the friction between surroundings and tether is kept minimum.



(a)



(b)

Figure 1. Rescue robot [24]
(a) Mine detection & removal (b) Walking robot for slopes

The other advantages of tether rescue robots include:

- The weight and the size of robot can be reduced significantly by reducing the capacity of onboard battery. The battery will be charged uninterruptedly through the tether.
- Tether can provide a highly reliable link for communication between control unit and robot. Communication architecture based on tether has several advantages over wireless technology. Wireless communication might cause the robots to interfere one other and might also pollute the wireless communication spectrum.
- In case of any malfunction, the robot can be easily dragged out from the debris.

Multiple robots can be deployed to a disaster scene for the fast rescue operations. These robots can work in parallel or independently to accomplish the rescue task in minimum frame of time [26]. It is difficult for a single robot to perform some tasks alone like overcoming high obstacles or heavy objects removing. In such scenarios, utilization of multiple robots can be an effective solution.

III. UNDERWATER ROBOTICS

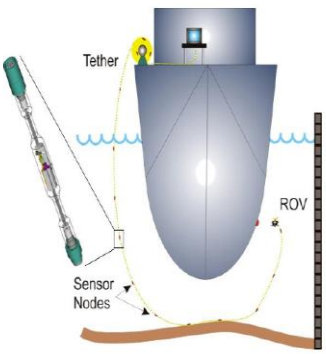
A large number of submersibles are operated in tethered mode rather than autonomous free swimming mode. The case of tethered operation can be continued for long period without any interruption or break and it also provides real time data transfer [27]. Applications of unmanned submersible and basic asset management principles should be more advantageous than using autonomous vehicles If tether management is done proficiently, the ability of submersible operations increases significantly. Tethered underwater water robotics can be used in: [28].

- Detection of underwater mines.
- Surveillance and location identification of planes and ships wreckage or other debris at the deepest ocean depths in fast and efficient way.
- Investigation of volcanic and hydrothermal activities in the deepest portions of oceans.
- Investigation and exploration of ultra-slow sea floor spreading geology, rock and fluid geochemistry and undersea creature biology
- Investigation and discovery of seismic, microbiological and geo-hydrological secretes, hidden in slopes of oceanic trenches in subduction zones.

Tethered underwater robots are commonly known as Remotely Operated Vehicles (ROVs) in the offshore industry. These ROVs are totally unmanned with large mobility and operated by expert aboard a ship. ROVs are connected through tether or umbilical cable. Tether consists of cables for electrical power supply and data and video signal transmission between vehicle and operator [29]. In "free swimming" operating method, ROVS buoyant on tether attached directly with the launching ship whereas in “garaged” operation method, ROVs operate on a tether connected with a heavy garage that is lowered from the ship. Both methods have their own advantages and disadvantages. The deep sea work, however normally carried out with a garage. Bowen *et al.* have explained a novel preliminary design of light-tethered Hybrid ROV (Fig. 2b) for exploring the deepest depths [28]. It first time provides the cost effective and efficient solution of systematic and regular access to the oceans as deep as 11,000 meters. The vehicle is also capable of untethered benthic survey operations as an

Autonomous Underwater Vehicle (AUV). For sampling operations, it can also operate as self-powered ROV. ROVs use very small diameter fiber optic tether. The purpose of the fiber optic tether is to only communicate high bandwidth data. It cannot serve as a power transmission line. Lower density floatation has the significant benefit if systems have lighter weights and smaller sizes. For example, an AUV that is smaller and lighter can travel further underwater. The tether comprises of fiber optics must be able to wound precisely into deployment box even with large length up to 20Km. The pressure and weight must be in tolerable range with respect to optical attenuation.

In a typical underwater tethered system, tether isolates the surface buoy movement from a subsurface float. The power is transferred from surface buoy to seafloor junction box, containing various sensors, via a cable. The sensor data received by surface buoy through tether is then transmitted to shore via satellite. Components of a typical underwater tethered system for underwater mines detection is shown in the following Fig. 2a.



(a) (b)

Figure 2. Underwater tethered system (a) Generic design [30] (b) HROV [31]

IV. SPACE ROBOTICS

In some degrees, satellites can be considered as robots because robot can be defined as “A machine used to perform jobs automatically, which is controlled by a computer” [32]. Secondly, satellite qualifies most of requirements of robot like it is artificially created and can sense the environment. Like robot, satellite has ability to make choices based on preprogrammed sequences. Similarly it can move or rotate in more than one axis.

A long wire, use to connect spacecraft with each other or with other objects, such as a space station, spent booster rocket or an asteroid, is named as space tether [33]. Space tethers are typically comprises of thin strands conducting wires or high-strength fibers. Different space objects can be connected with tether to transfer momentum and energy from one body to the other. As the results this connection reduces the consumption of propellant by providing space propulsion. Space tethers can also offer capabilities for various applications including formation flying tethers, electrostatic tethers, momentum exchange tethers and tethered rovers.

A planet exploration unit conventionally comprises of a lander and a rover. A classic rover contains the Drilling & Sampling Subsystem (DSS) to collect the samples from the ground. Camera mounted on the lander is used to navigate the rover. The rover and lander are connected by tether for both communication and power purposes. Initially, the rover ejects from lander and the lander camera guides it to the particular area. It drills and extracts the samples of planetary soil and finally proceeds back to the lander. Operational scenario of rover is illustrated in the Fig. 3. Tether can also be seen in the figure.

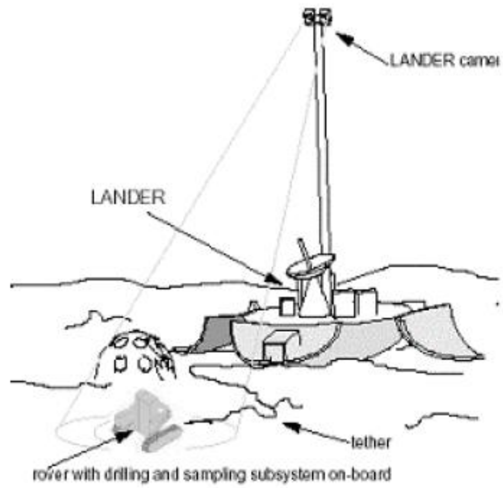


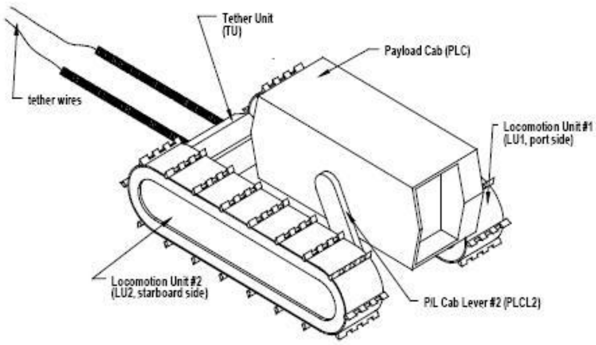
Figure 3. Setup of a typical lander-rover system

Most famous planetary rovers using tethers are Nanokhod, MRoSA 2 and PROP-M planetary rovers, described in more detail below.

A. Nanokhod

The Nanokhod micro rover was developed by ESA to meet the requirements of space exploration missions. Sophisticated design of rover accommodates the scientific instruments in the central payload cab that has two Degrees of Freedom (DOF). Tank like tracks are used for the locomotion purpose. Thin tethers connect the lander and rover for power supply and data communication. The navigation and control of rover is semi-autonomous. It used lander 3D model of the land elevation, attained by means of lander panoramic camera. The peak consumption of electrical power is only 3W and thermal control is completely passive. The rover payload mass is about 1100 grams. Figures 4a shows the Nanokhod isometric view whereas Nanokhod in operation is depicted in Fig. 4b.

The actuation unit of Nanokhod breadboard consists of left and right track locomotion motors, level articulation motor, payload articulation motor and LED indicators. LEDs are used by lander to trace the location of the lander. The rover has different sensors to measure payload cap angle and rover motion. It also contains 6 contact switches at the front of payload cap.



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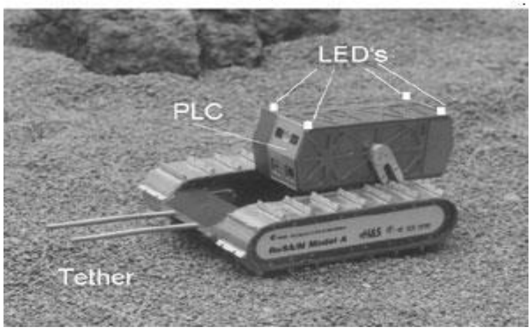

(b)

Figure 4. Nanokhod [34] (a) Isometric view (b) Rover

B. MRoSA 2

In 1998, ESA initiated the Micro ROSA project. The overall objective of the project is to develop a Robotic Sampling System based on Nanokhod. This means to develop a drill capable of subsurface sampling (down to 2 meter depth) and modifying Nanokhod to be able to operate as a platform for this drill. The project was carried out in Finland by HUT, SSF and VTT. In 2002, the project got continuation in the form of MRoSA2 upgrade project. This also includes SW upgrades due to rover's tether reel repair to ensure smooth reeling [35]. In MRoSA 2, the only improvement to the Nanokhod design from the requirements side was that the tether should be rewindable [36]. MRoSA 2 is depicted in Fig. 5. The rover for this thesis (ROSA) has same structure as that of MRoSA but it does not currently have Drilling and Sampling Subsystem (DSS).

Figure 5. MRoSA 2 rover in operation [34]

ROP-M

The Russian Mars lander contains a tiny walking robot, "PROP-M" [37]. Because it did not have its own power source, it was tethered to the lander. The tether was 15 m of length and it also carried the communication line. The robot carried two instruments: a radiation densitometer (called "GEOHI" RAS) and a dynamic penetrometer. The rover was onboard Mars-2 and 3, and later Mars-6 and 7 landers, which all unfortunately failed. The "ski-walking" rover is shown in Fig. 6 Mass of the rover was 4.5 kg whereas the dimensions were 215x160x60 mm. Travel speed was one metre per hour and the rover consumed 5 W of power. Russian Lavochkin Association produced the rover. As shown in the Figure, the main frame of the PROP-M had a small protrusion attached with a small square box at the top of the body. The frame of the rover elevated marginally above the surface with the help of 2 widespread flat skis.

Obstacle and hurdle detection strip at the front of the rover can also be viewed in the Figure. A robotic manipulator arm landed the rover on the planet surface. The rover moved in the coverage area of lander cameras. It was programmed to stop every 1.5m to make measurements. The record of movement traces in Martian soil also provided material properties.

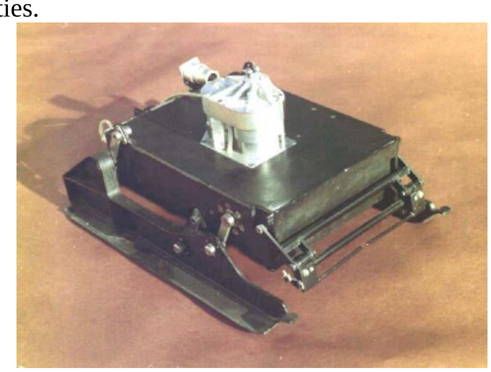

Figure 6. The PROP-M ski-walking rover

V. OTHER TERRESTRIAL TETHERED ROBOTICS

Tether also finds its applications in hyper-tethered robots, petroleum tank inspection robots, volcanic exploration robots and a number of other terrestrial robots.

A. Hyper-tether applications

Hyper-tether concept has been emerged as a result of recent advancements of tethered connections that permit tethering among several kind mobile robots with the environment and with animals and humans [38]. The core function of hyper-tether is to dynamically control the tether's length and/or tension. It also considers tether anchoring, launching, data communication cabling, power delivery, and in-built trajectory command generation abilities.

The intrinsic property of walking machines is their ability to move over rough lands but on the other hand, their payload capacity is limited. In contrast, wheeled or crawler robots offer heavy payload capacity but their performance degrade on steep slopes and irregular terrain. A load transportation system is shown in Fig. 7a, which combines the advantages of both kind of mobile robots. In such mechanism, the walking robot firmly fixes itself to the ground at the top of the hill and pulls the crawler robot upward with a tether. The descending motion can also be accomplished in the same way.

Similarly, hyper-tether hardware can assist humans or robots to move on steep slopes, as illustrated in Fig. 7b. It is worth to note that the base interface is attached on the moveable platform rather than fitting it on the land. In such configuration, friction between the environment and the tether is obviated as the tether is reeled in or out from the winch with the movement of platform.

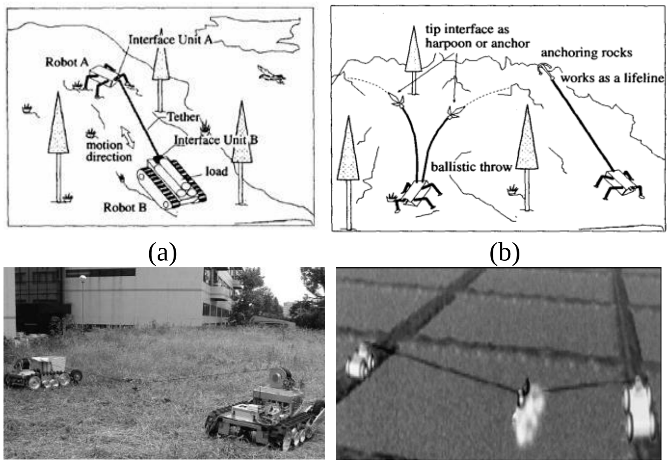

Figure 7. Hyper-tether applications [38]
(a) Load transportation (b) Rock anchoring
(c) Field scanning (d) Spraying

Other potential applications for hyper-tether include: material transportation, micro-rovers locomotion in micro-gravity locations, stable and steady movement on steep slopes, weed removal, mine detection and removal, garden grass trimming of vast areas, such as baseball and football fields and golf courses, transportation of goods in hilly areas, construction and forestry works and spraying of chemicals in agricultural lands.

B. Petroleum tank inspection robotics

Wired communication links are the only means that ensure uninterrupted communication with the robots working in enclosed environment such as tanks and pipes [39]. The tether can be used for deployment of robots. For example, to lower the robot through an opening of an oil tank, tether could be a useful tool. In the same way, tether can retrieve the robot in case of malfunction.

Example of tethered robots for tank inspection system includes Neptune system [40]. It is a mobile robotic system specifically designed for the inspection of Above-ground Storage Tanks (ASTs) containing petroleum products. It is almost impossible for human to enter such places. This system eliminates the need of human walkthrough examination of tank. The can enter even in the filled ATS and sensors collect all required data.

The overall system consists of a crawler robot (Fig. 8), in-tank acoustic positioning console, deployment pod and an external control unit. The robot is equipped with ultrasonic and visual sensors. The remote control unit is compatible with custom developed and commercial software for planning, display and control tasks.

The sensors attached on robot consists of miniature color CCD camera with low-temperature LED and halogen bulbs to lighten the track in front of the crawler robot. The ultrasonic sensing probe is mounted at the rear end of the vehicle. It comprises of eight in-line transducers attached with a self-leveling magnetic-wheel trolley. The on-board camera record the visual data of every weld seam of storage tank and the ultrasonic sensors record and map the data of bottom plats thickness. The robot is operated on 48 VDC that is supplied from outside 300VDC power source by the tether. Robot has on-board DC to DC converters to generate other required voltages.

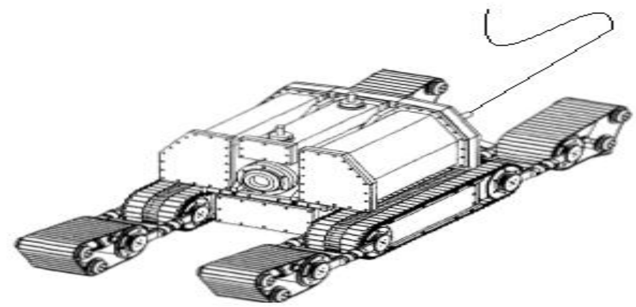

Figure 8. Neptune: Tethered crawler [40]

C. Volcanic exploration robotic

Designing of tether robotic system for volcano exploration is considered the most challenging case-study. Eight-legged rappelling robot Dante II is specially designed for volcano exploration [39]. Like mountaineer climbing rope, Dante II uses tether as a support to move on steep slopes. Tether also connects the robot with satellite communication station and generator located at the rim of volcano. The satellite station communicate the data between operators and robot. 300m long tether is reeled in and reeled out by an onboard winch drum (Fig. 9).

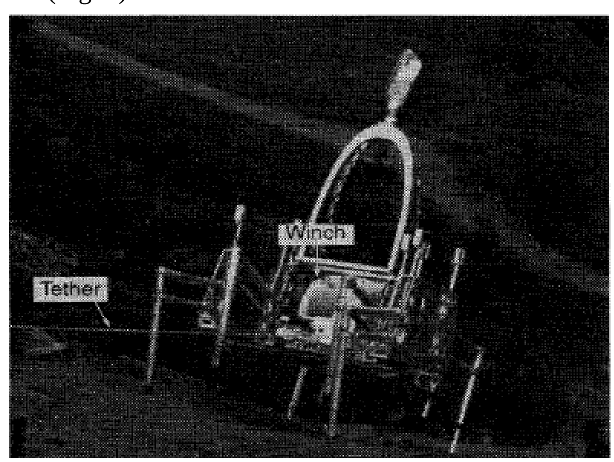

Figure 9. Dante II at a field test [39]

To keep a proper tether tension during the entire motion cycle, the robot coordinates tether payout with leg motion. This is very important strategy to cop up with the abrupt changes in steep slope. Tether also helps to distribute equal load on the robot leg.

D. Non-robotic tethered applications

Non-robotic tethered applications include meteorological and weather monitoring systems and underwater exploration [39]. In weather monitoring system, a tether is used to anchor weather balloon with the ground unit. The tether also establishes power and communication link between balloon and control unit. Tethered meteorological kites have been also used for number of reasons. These kites provides cheap and stable platform. They can be kept aloft continuously for several days to monitor atmosphere. They can lift scientific equipment to the dizzy heights of several kilometers. They can work remotely over land, sea or ice.

Beyond collecting climate data, kites are also used by some researchers to lift insect traps high into the air to study insect migration. A car winch is employed to fly the kite in a temperate weather [41]. The capstan is attached to the elevated wheel of the car to control the kite and tensions tension (Fig. 10). The tether can be reeled out by putting the car in reverse. If the car is parked, the line stays still whereas putting the car in forward reels in the tether. In a cold weather, an electric winch is used. The winch is powered by an electric generator. A WindTRAM (Tether Rover for Atmospheric Measurements) moves up and down the kite equipped with scientific devices. The wing angles are adjusted through automatic control. The altitude of kite can be measured very precisely by employing the differential GPS receivers on kite and ground.

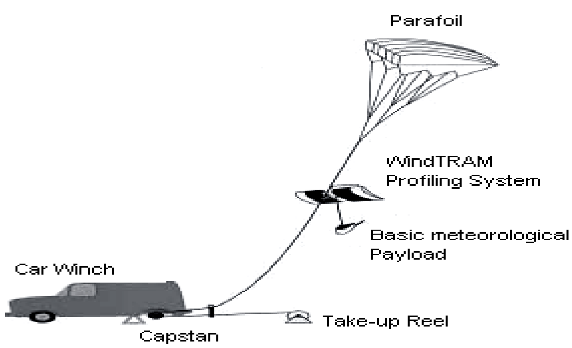

Figure 10. Tethered meteorological kite [41]

VI. CONCLUSIONS

With the advancement in technology, the demand of robotics has increased significantly in different areas of research, exploration and innovation. Robotics also finds applications in warfare and rescue operations. Some of these applications require small and compact mobile robot to accomplish tasks in congested and tighter locations. Tethering can considerably reduce the size of robots by eliminating the need of onboard power source. Tethering also provides reliable communication link between robot and operator. Tethered systems can also be used to assist the locomotion of robots on rutted surfaces ad steep slopes.

In this paper, an application based survey of tethered robotic platforms has been discussed. These applications include rescue systems, underwater tethered operations and space exploration. Other terrestrial applications like hyper-tether systems, tank inspection and volcano exploration have also been discussed. Finally a brief note on non-robotic tethered based applications has been presented. This paper is anticipated to boost the nouveau research in the area of tethered robotics. The review will help researchers to develop advanced platforms in this field.

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