ENTANGLEMENT DETECTION OF A SWARM OF TETHERED ROBOTS IN SEARCH AND RESCUE APPLICATIONS

T. R. Vishnu Arun Kumar and R. C. Richardson
School of Computer Science, University of Manchester, Manchester, United Kingdom

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Abstract: In urban search and rescue (USAR) applications, robots play a pivotal role. As USAR is time sensitive, swarm of robots is preferred over single robot for victim search. Tethered robots are widely used in USAR applications because tether provides robust data communication and power supply. The problem with using tethers in a collapsed, unstructured environment is tether entanglement. Entanglement detection becomes vital in this scenario. This paper presents a novel, low-cost approach to detect entanglement in the tether connecting two mobile robots. The proposed approach requires neither localization nor an environment map. Experimental results show that the proposed approach is effective in identifying tether entanglement.

1 INTRODUCTION

USAR is a time-critical process, which involves complex and hazardous environment. Secondary collapse, confined space, presence of fire and poisonous gas in the environment pose serious threats to the human and canine rescuers. Thus, robots become inevitable in the field of search and rescue. Mobile Robots can be used for a variety of tasks such as localization, communication, victim search, biomedical monitor delivery, environment monitoring and reconnaissance. It is desirable to deploy a swarm of robots as the survival rate of the victims falls drastically after 72 hours.

Untethered autonomous robots depend on wireless communication for information exchange. When such robots are employed simultaneously in the same area, issues such as interferences with other systems, data security and international band differences will arise as stated in (Fukushima et al.). Tethered robots are used in a variety of applications in ground, under-water and space environments (Fukushima et al.). During recent times, tethered robots are being employed in search and rescue because tethers inherently provide robust data communication and uninterrupted power delivery (Fukushima et al.), (Hert et al., 1999). Tethers can be used for navigating the robots through steep slopes (Fukushima et al.) and also for pulling the robot out when it gets stuck into debris (Perrin et al.).

When a swarm of tethered robots is employed in USAR environment, the tether might get entangled with the obstacles or fellow robots. Entanglement detection becomes an important problem that needs to be addressed. Despite this, the merits of using tethers make them a valid option even in search and rescue scenario. Traditionally there are different techniques to tackle entanglement detection. Most of them need the robot to localize using an environment map, which is then used to detect the existence of tether entanglement. Navigation planning could be done in such a way that there is no tether entanglement (Hert et al., 1999). A method to plan the shortest path for a tethered robot to a destination point has been discussed in (Xavier, 1999).

In this paper, a novel, low-cost technique to detect tether entanglement has been proposed. This technique does not need the swarm of robots to be localized. It does not require any environment map. Section 2 discusses related work on localization and map building in USAR. In Section 3, the tether entanglement detection hardware is explained. Section 4 throws light on experimental results and Section 5 deals with the characterization of tether entanglement using the experimental results. In Section 6, a static model of tether is derived and the experimental results are analyzed using the model. Section 7 and 8 discuss current work and conclusion respectively.

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2 RELATED WORK

In USAR, communication and power supply play crucial role. In case of autonomous robots using wireless communication, the information exchange is always noisy because of the thick concrete and steel structures present in the search and rescue environment (Perrin et al.). Also untethered robots carry on board power supply for their operation. This limits the life time of the entire system. So tether based multi-robot systems are preferred over untethered robots in search and rescue scenario. In a tether based multi-robot system, a robot can detect tether entanglement based on its pose in the environment map and the pose of the fellow robots in the same map. This technique is often referred to as Simultaneous Localization and Map building (SLAM) (Wijesoma et al., 2004).

One of the approaches for SLAM is to use Inertial Measurement Unit (IMU) for localization and Global Positioning System (GPS) for map building. An Inertial Navigation system has errors rising from factors like bias, scale factor uncertainties, misalignment errors and noise (Sukkarieh et al., Volume 19). Also in an uneven terrain, gyrometer readings tend to be very noisy. Fault detection and fault isolation form an integral part of an IMU as stated in (Sukkarieh et al., Volume 19). In search and rescue scenario, GPS becomes futile as discussed in (Gustafon et al., 2005), (Cheng et al., 2004), and (Ramirez-Serrano et al., SSRR).

Vision based approaches, which rely on landmarks are used to localize the robot (Saeedi et al., 2003), (Ramirez-Serrano et al., SSRR). As search and rescue environment is complex and unstructured, landmark based approaches are not efficient (Cheng et al., 2004). The same reason can be applied to (Saeedi et al., 2003) in which a vision based approach for 3D localization and tracking has been proposed. In this approach, distinctive scene features extracted from the environment are used for localization, but uncertainty in perception rising due to different regions appearing similar is an issue to be addressed.

The concept of Intelligent Dynamic Landmarks is discussed in (Ramirez-Serrano et al., SSRR), wherein some members of the robot group act as portable landmarks for other robots to localize. In (Gustafon et al., 2005), a swarm of robots have been employed to achieve localization and target identification. Line of sight approach is adopted to localize heterogeneous teams of robots in (Grabowski et al., 2004).

In order to detect tether entanglement, most of the approaches need the robots to be localized and/or an environment map. In this paper, a novel tether entanglement detection technique has been proposed that eliminates the need for localization and environment map.

3 ENTANGLEMENT DETECTION HARDWARE

The essence of this approach is that by recoiling tethers and monitoring the force across the tether during this process, entanglements, snags and chafing effects on the tether can be detected. The proposed system consists of two components (i) the tether winding unit that pulls up tether slack (ii) a sensor to detect horizontal forces across the tether. The principle described here is to be applied to swarms of interlinked tethered robots.

3.1 Tether Winding Unit (TWU)

Tether Winding Unit comprises of a pair of wheels tightly coupled with a spring. One of the wheels is driven by a 6 volt-5 Watt DC Motor. The tether passes between a pair of wheels as shown in the Figure-1. This unit is mounted on one of the robots (Robot-A). There is an automatic wire coiling system on the robot, which would hold one side of the cable.

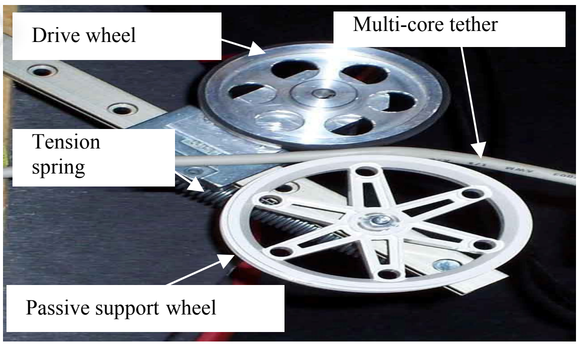

Figure 1: Tether Winding Unit (TWU).

3.2 Force Measurement Unit (FMU)

This unit comprises of a force sensor to measure the force exerted on the tether. This unit is mounted on the other robot (Robot-B). Tether entanglement detection is carried out in the following steps:

Step-1: The tether connecting two robots is pulled taut using the TWU.

Step-2: During that process, the horizontal force exerted on the tether is measured using the FMU.

Step-3: Based on the pattern in which the force exerted on the tether increases, it can be identified whether the tether is snagged by an obstacle or not.

4 EXPERIMENTAL RESULTS

Tether Entanglement can be detected experimentally through *Snag Test,* which makes use of TWU attached to one robot and FMU attached to the other robot. An open loop test is performed under four different scenarios with or without obstacles. The input voltage and the output force are recorded during each test. Each of the four scenarios depicts different levels of friction and different tether dynamics involved when the tether is being pulled. The scenarios are as follows:

Case-A is the scenario in which the tether is freely hanging and there is no entanglement. Case-B models the scenario in which the tether is stuck in rubble and is subjected to friction at discrete points along its length, as a result of which there is an uneven movement when it is being pulled. In Case-C, as the tether is wound around a pillar-like object, the friction would be so high that the TWU would not be able to hold the tether taut. Case-D depicts a scenario in which the tether is bent by pillar-like object and there is slow and steady movement of the tether when it is being pulled. This is because the friction is uniform through out the length of contact with the obstacle. Figure 2 shows a snapshot of rubble and pillar-like objects respectively.

Figure 2: Snapshot of rubble and pillar-like objects.

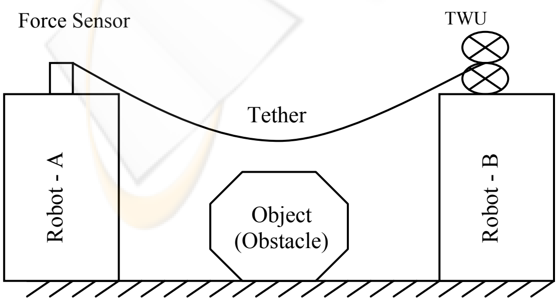

Figure 3: Schematic of Experimental Setup.

The snag test is conducted using unequal square wave pulse, which excites the system so that the dynamic effects of the tether being pulled are tested on different lengths of the tether at different stages of the experiment. Also the pulsing signal would excite the stick-slip friction. A schematic of the experimental setup is shown in Figure-3.

The force sensor readings are plotted against time for all the four scenarios along with the unequal square wave input signal as in Figure-4. Initially as the input voltage is zero, the force exerted on the tether remains a constant. After 6000ms, the voltage raises to +2 V. This is reflected in the graph as steep raise in the force value. It is also observed that there is a lag between the time of application of the voltage pulse and the time at which the force value starts to raise. This is because the force exerted on one end of the tether by TWU has to reach the other end of the tether containing the FSU.

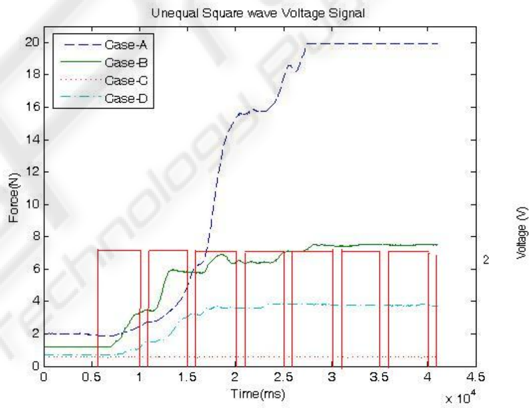

Figure 4: Input-Output Graph.

5 CHARACTERISATION OF TETHER ENTANGLEMENT

In Figure-4, the force value for Case-A raises steeply whenever the voltage pulse is applied because the tether is hanging freely. For Case-B, there is uneven raise in force value, as the friction from the rubble acts at discrete point throughout the length of contact of the tether. Case-C has no effect in force value, as the tether is completely snagged and the friction is so high that it is not possible for the TWU to pull the tether. For Case-D, as there is uniform friction throughout the length of the tether, there is a smooth transition in the force value.

The force curves are analyzed using three different methods namely Range of force analysis, Area under the curve analysis and Static Model

Analysis. From these analyses, an attempt has been made to identify the type of snag from the force sensor readings.

5.1 Range of Force Analysis

In this method, the force curve is preprocessed so that any offset in force is eliminated. From the force curves, it is very evident that when the tether is not snagged by an obstacle (Case-A), the TWU holds the tether taut and the maximum force is around 18 N. For all the scenarios where the tether is entangled, the maximum force is around 6 N as shown in Table-1. Thus Force Range can be used as a parameter to model the type of snag.

5.2 Area Under Curve Analysis

If there are false spikes in the force curve due to factors like slippage, drift, small object falling on the tether, analysis using range of force would be misleading. Area under curve analysis would reduce such effects. After eliminating the offset from the curves, the area is calculated as summation of the product of the time interval (20ms) and corresponding force value. The mean area of the force curve for the three samples is calculated for all the four different scenarios and listed in Table-1.

It could be seen that Case-A has maximum area of around 400 square units. For Case-B and Case-D the area is around 200 and 100 square units respectively. Case-C has least area of less than unity. Thus for a given input signal, based on the area under the force curve, the type of snag can be determined. For this analysis, time duration of the test plays a significant role, as the area of the curve is directly proportional to time.

Table 1: Average values of Force Range and Area under Curve.

Case	Force Range (N)	Area under Curve (square units)
A	18.195	400.0576
B	6.627	173.9507
C	0.124	0.1794
D	3.289	89.2996

6 TETHER MODELLING

From the experimental results it was observed that the system is non-linear. This is evident from the force curves in Figure-4. A non-linear model of the system would give better insight into the behavior of the system. A static model of the Tether Entanglement Detection System (TEDS) is shown in Figure-5. It comprises of two robots (Robot-A and Robot-B) connected using a tether. Robot-A has the tether linked with FMU. Robot-B has the tether passing through TWU. The following are the parameters, which influence the model.

F_{pull} - Horizontal pulling force (N)
θ_{sag} - Sag angle of the tether (radian)
α_{wheel} - Angular Velocity of drive wheel (radian /s)
L_c - Half of the catenary length of the tether (m)
L_h - Half of the horizontal length of the tether (m)
a - Distance between the vertex and the axis of the catenary curve (m)
Z_w - Distance of the top of the catenary curve from its axis (m)

6.1 Static Model of Freely Hanging Tether - Derivation

A static model of the tether based robot system has been derived. It is assumed that the dynamic effects of the tether are negligible because the angular velocity of the wheel α_{wheel} is low. It is also assumed that the mass is evenly distributed throughout the length of the tether and the curve created by the freely hanging tether is a catenary curve. A catenary curve is the shape created by a chain-like object fixed on both ends and hanging freely under the force of gravity. The model can be used to determine the horizontal pulling force (F_{pull}) acting on the tether and the sag angle (θ_{sag}) of the tether (Flugge, 1962).

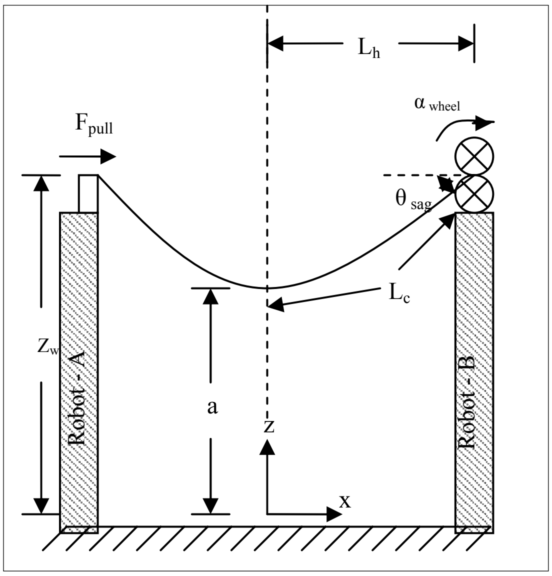

Figure 5: Tether Entanglement Detections System (TEDS) Model.

6.1.1 Horizontal Pulling Force Derivation

The horizontal pulling force (F_{pull}) is given by the following formula:

$$F_{pull} = q \times a \quad (1)$$

where
q – weight per unit length of the tether (N/m)

In order to determine '*a*', the following formulae are used.

$$L_c = L_{ini} - \left(\left(\frac{R}{2} \right) \times \alpha_{wheel} \times t \right) \quad (2)$$

$$L_c = a \times \sinh\left(\frac{L_h}{a} \right) \quad (3)$$

where
L_{ini} – Half the initial length of the tether (m)
R – Radius of the wheel (m)

Formula (2) is used to deduce the value of L_c. This value is used in formula (3) to find out the value of '*a*' by creating the following non-linear equation:

$$f(a) = L_c - \left(a \times \sinh\left(\frac{L_h}{a} \right) \right) = 0 \quad (4)$$

Newton-Raphson iterative method is used to solve the above equation. For that the derivative of *f(a)* is needed.

$$f'(a) = -\sinh\left(\frac{L_h}{a} \right) + \left(\left(\frac{L_h}{a} \right) \times \cosh\left(\frac{L_h}{a} \right) \right) \quad (5)$$

Assume the first guess $a_0 = L_h$, then

$$a_1 = a_0 - \left(\frac{f(a_0)}{f'(a_0)} \right), \; a_2 = a_1 - \left(\frac{f(a_1)}{f'(a_1)} \right) \cdots$$

This is repeated until

$$\left(\frac{|a_{k+1} - a_k|}{|a_{k+1}|} \right) < threshold \quad (6)$$

Threshold can be lower than 0.00001. Lower the threshold higher is the accuracy of the value of '*a*'. The value of a_{k+1} is used as the value of *'a'* in formula (1).

6.1.2 Sag Angle Derivation

The formula for Sag angle is as follows:

$$\theta_{sag} = a\cos\left(\frac{a}{Z_w} \right) \quad (7)$$

where

$$Z_w = a \times \cosh\left(\frac{L_h}{a} \right) \quad (8)$$

6.2 Analysis

The static model is verified experimentally by measuring the force sensor readings for different catenary length of the tether (L_c) keeping the distance between the robots (L_h) as constant. Then a graph is plotted with x-axis containing the ratio between L_h and L_c and y-axis containing the corresponding force readings. In the same graph the force curve predicted using the static model for the same value of L_h is drawn as shown in the Figure-6. It is observed that the actual force readings are very close to the predicted values. This validates the static model.

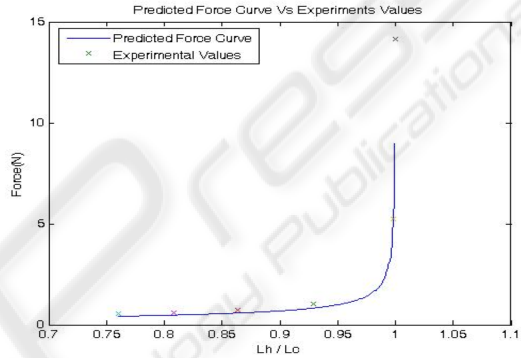

Figure 6: Predicted Force Curve Vs Experimental values.

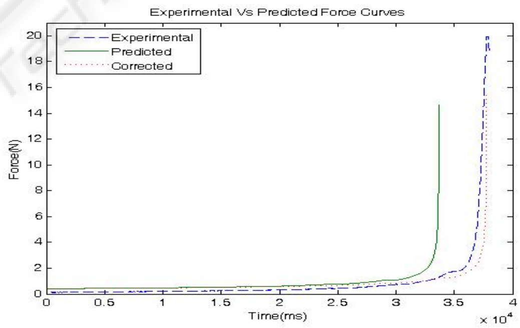

Figure 7: Actual Vs Predicted Vs Corrected Force Curve.

Figure-7 shows the actual force readings and those predicted using the static model for Case-A. The predicted force curve closely follows the pattern of the actual force curve except that it lags in time. This is because the angular velocity of the drive wheel will reduce when it is running under load (tether passing through the wheels) compared to no load condition. This is verified by simulating the predicted force curve with 90% of the measured angular velocity. The corrected curve matched very closely to the experimental force curve as shown in Figure-7. Another reason for the time lag could be attributed to slippage of the tether. An optical encoder could be attached to the wheel to measure the tether length, as it eliminates the time lag error.

From the above three analyses, it is evident that the static model analysis is more promising than the other two methods in terms of providing an accurate model of freely hanging tether. Such a model can be used to predict the force curve for freely hanging scenario and the predicted curve can be compared with the experimental curve. Based on the error between the two curves, it could be identified whether the tether is freely hanging or snagged with obstacles. The static model can also be used to identify different types of snags if dynamic effects are introduced into it. One such approach could be friction modeling.

7 CURRENT WORK

Currently friction modeling is being investigated to understand the dynamic effects of the system. Also a robust and low-cost 3D localization strategy for a swarm of tethered robots is being developed. This technique does not require an environment map for localization. It includes a tether length measurement unit (TLMU) and a tether orientation measurement unit (TOMU) to localize the robot in 3D space. TLMU comprises of an optical encoder attached to the passive wheel of the TWU to measure the length of the tether. TOMU consists of a joystick attached to the end of the TWU to measure pitch and roll of the tether.

8 CONCLUSION

In this paper a novel, low-cost and robust system, which does not require localization or environment map to detect tether entanglement has been proposed. A static model has been derived for the proposed system. Experiments have been conducted to verify the validity of the approach. The results are analyzed using three different methods. From the analyses it is clear that the static model analysis is a promising way of detecting entanglement because it clearly identifies the scenario in which the tether is freely hanging.

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