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Investigation to Enhance the Actuation Force Transmission of Cable-Driven Continuum Manipulators with Tethering Lines

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Inspecting confined spaces at elevated locations such as pot bearing housings in railway viaducts are challenging. Elevated work platforms are typically used to hoist people and equipment to conduct the inspection manually, which are often time-consuming, laborious and at times, physically inaccessible. A unique combination of an aerial drone, integrated with a lightweight cable-driven manipulator and a ground unit containing the cable winching actuators and the motion control system, is proposed to overcome this challenge. The winching cables in the manipulator are routed from the ground unit using tethering lines based on the Bowden cable concept. However, this results in high loss in force transmission due to the excessive amount of both static and dynamic friction between the cables and the sheath over long lengths, typically 10 to 15 metres, as required by the application scenario. This paper focuses on the investigation of designing tethering lines with high force transmission, through the use of Design-of experiments to identify relevant and dominant design variables for design optimization. The identified design variables consisted of the materials for both sheath and actuation cables, to the type of lubricant used to coat the sheath, the cable pretension and the cable speed. Based on an experimental test-bed that compared the cable tension readings, before and after, passing through the tethering line, the conclusion indicated that an enhanced design results with the use of SP41 Bowden sheath, an uncoated steel cable and applying silicone lubricant on PTFE tube, which improved the force transmission efficiency by 23%, 18% and 2%, respectively. Also, reducing the cable pretension from 25N to 9N and reducing the cable speed from 30mm/s to 5mm/s improved the force transmission efficiency by 1% and 5%, respectively. These results facilitated in selection appropriate materials for the tethering line and cable winching settings, which culminated in enhancing the force transmission through the winching cables.

NOMENCLATURE

R_k = Force transmission efficiency
T_{in} = Cable tension before the sheath
T_{out} = Cable tension after the sheath

1. Introduction

Continuous monitoring and maintenance of infrastructure and building structures in rail transport such as pot bearing housings in railway viaducts (see Fig. 1), are critical to minimize any breakdown in critical services. Currently, significant portion of such monitoring work located at elevated locations are carried out using aerial work platform (AWP). An AWP is a mechanical device that is used to hoist and provide temporary access to people and equipment to reach inaccessible areas at heights. It is also known as an elevated work

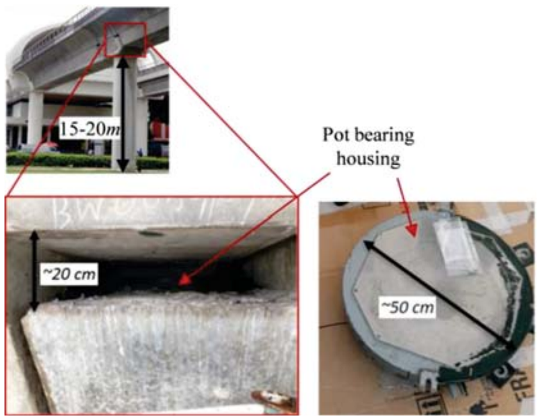

Fig. 1 Pot bearing housing in railway viaducts

platform (EWP), bucket truck or cherry picket [1]. The use of AWP is often time-consuming, laborious and at times, physically inaccessible, which presents a gap to be addressed to enhance the productivity in conducting such maintenance tasks. To address this gap, a unique combination of an aerial drone, integrated with a lightweight cable-driven continuum manipulator and a ground unit containing the cable winching actuators and the motion control system, is proposed (see Fig. 2). The winching cables in the manipulator are routed from the ground unit using tethering lines based on the Bowden cable concept. Bowden cables are flexibles cable with the actuation cables moving inside a sheath and thereby transmitting the pulling force. The sheath is required to have a high compressive strength to prevent buckling under a high compression force. By using Bowden cables, the actuators can be placed away from the manipulator which helps to reduce manipulator weight. This lightweight feature makes Bowden cable attractive to be used in wearable robots and medical devices [2] [3] and a good candidate to be used in cable-driven manipulators, especially in this setup where the manipulator is to be attached to the aerial drone.

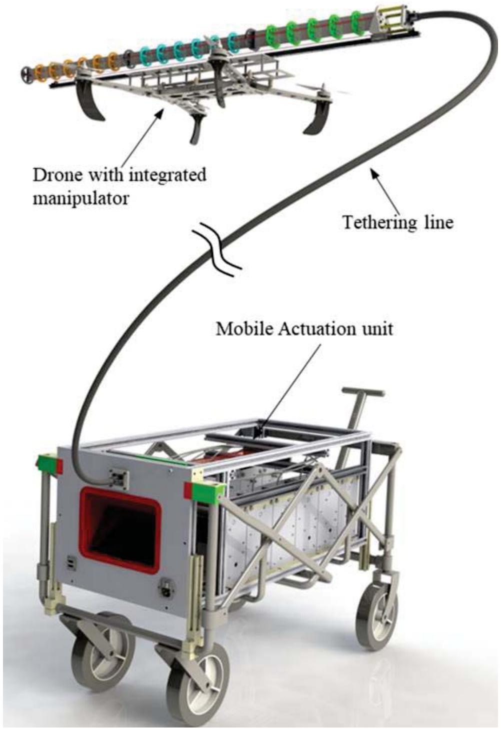

Fig. 2 Cable-Driven Continuum Manipulators with Tethering Lines system

However, Bowden cables have an inherited drawback of having high friction between the cables and the sheath, causing high loss in force transmission over long lengths, typically 10 to 15 metres, as required by the application scenario (see Fig. 1). Authors in [4][5] reported force transmission efficiency of Bowden cables can be as low as 5%. Friction depends on many parameters, such as the cable and sheath material, lubricant used, curvature of the tethering line, cable pretension, cable speed, cable length, as well as contact interaction parameters, leading to difficulty in performing analytical friction analysis of the Bowden cable.

In the following sections, this paper will detail the experimental method to investigate the identification of dominant input variables, as well as the effect on the force transmission efficiency and static friction pretension ratio, followed by presentation of the key results that will facilitate in the design of tethering lines with better actuation force transmission.

2. Overview of the Design of Experiment

The design of experiment (DoE) is a systematic approach to understanding how process and product parameters affect the response variables [6]. It is used to determine which parameters are significant in contributing to the actuation force transmission efficiency and used to decrease the number of tests. This DoE investigated the effects of nine variables, including material and stiffness of cables and sheaths, cable speed, pretension, clamp distance, clamp orientation and cable length on the force transmission efficiency and static friction pretension ratio.

After a further analysis, the identified design variables consisted of the materials for both the sheath and the actuation cables, the type of lubricant used to coat the sheath, the cable pretension and the cable speed (see Table 1). The high and low level of input variables were selected based on the preliminary investigation results. Two types of sheath material were used in the experiment, namely (i) Shimano SP41 with inner diameter of 1.5 mm and outer diameter of 4mm, and (ii) Polytetrafluoroethylene (PTFE) tube with inner diameter of 1.5 mm and outer diameter of 3mm. The Shimano SP41 by default has been pre-lubricated with a special silicone grease. The two types of the actuation cable used in the experiment were 7x7 stainless steel cable and 7x7 PVC-coated. Both had an outer diameter of 1mm. The effect of lubricant was also investigated by applying WD-40 Silicone for the high level and no lubricant applied for the low level. Different cable speed as required in DoE was achieved by controlling the pulse cycles period in Arduino. Different cable pretension were obtained by changing the counter-weight (see Fig. 3). According to number of input variables, a 2^5 (= 32) full factorial design was used to test the effect of input variables on the output variables.

Actuation force transmission efficiency, defined by the comparison of cable tension after passing the sheath (output) with cable tension before the sheath (input) as written in equation (1) was used as a criterion in evaluating output variables.

Table 1 Low and high levels of input variables

Input variables	*Low Level (-1)*	*High Level (1)*
Material of sheath	PTFE 1.5 x 3	Shimano SP41
Material of cable	7x7	7x7 PVC coated
Lubricant	No Lubricant	WD-40 Silicone
Cable Pretention (N)	9	25
Cable Speed (mm/s)	5	30

$$R_k = T_{out} / T_{in} \quad (1)$$

The output tension would differ from the input tension because of friction along the cable, which changed with the input variables in Table 1. The aim of the experiment was to identify the input variables that would result in a high actuation force transmission effciency in the tethering lines.

3. Experimental Setup

An experimental setup was designed to measure the cable tension before and after passing the sheath as shown in Fig. . The setup consisted of two frame units, one unit to measure input cable tension and control cable speed and another unit to measure output tension and to apply cable pretension. Both frames clamp the sheath to hold it in position. The distance between the frames was 500mm while the sheath length was 1000mm. This combination of sheath length permits the sheath to bend in one loop and simulate the curvature experienced in an actual on-site scenario. Cable tensions were measured using tension load cells with 1kN rating and 1N resolution. The actuation cable could be reeled-in or reeled-out by the winching unit using stepper motors. Cable tensions were measured during the reel-out condition which was due to the weight hanged at the output frame, while the cable moved with a speed defined by the stepper motor controller. The cable tension readings (input and output) during the test were recorded for a 100 mm motion and plotted. A typical plot of the cable tensions is shown in Fig. . Cable tensions were relatively flat during the test, and the average value of the force transmission efficiency was calculated based on equation (1).

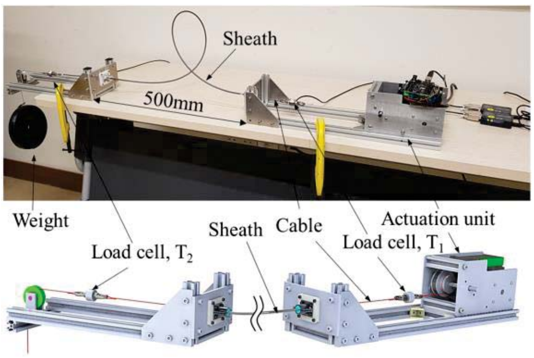

Fig. 3 Experimental setup

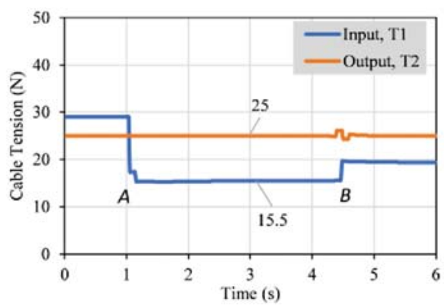

Fig. 4 Typical plot of the cable tension readings. Reel out is started at point A and moving as far as 100mm, before stopping at point B.

4. Result and Discussion

Table 2 showcased the obtained results of the force transmission efficiency, R_k under a total 32 (i.e., 2^5 full factorial design) different test permutations. The data in Table 2 was processed to obtain the main effect of each input variables, where the effect was defined as the difference in the average response between the two levels. A positive effect meant that the force transmission efficiency increased as the input variable varied from its low to its high value.

Table 2. Design of experiment matrix and experimental results

No	Input variables					Output variables		
	Material of Seath	Material of Cable	Lubricant	Pre-Tension (N)	Cable Speed (mm/s)	T1	T2	Rk = T2/T1
1	SP41	7x7	No Lubricant	9	5	9	5.8	64.4%
2	SP41	7x7	No Lubricant	9	30	9	6	66.7%
3	SP41	7x7	No Lubricant	25	5	25	18	72.0%
4	SP41	7x7	No Lubricant	25	30	25	17.7	70.8%
5	SP41	7x7	WD-40 Silicone	9	5	9	4.7	52.2%
6	SP41	7x7	WD-40 Silicone	9	30	9	4.2	46.7%
7	SP41	7x7	WD-40 Silicone	25	5	25	16.4	65.6%
8	SP41	7x7	WD-40 Silicone	25	30	25	15.1	60.4%
9	SP41	7x7 PVC-coated	No Lubricant	9	5	9	4.4	48.9%
10	SP41	7x7 PVC-coated	No Lubricant	9	30	9	3	33.3%
11	SP41	7x7 PVC-coated	No Lubricant	25	5	25	16	64.0%
12	SP41	7x7 PVC-coated	No Lubricant	25	30	25	11	44.0%
13	SP41	7x7 PVC-coated	WD-40 Silicone	9	5	9	4.3	47.8%
14	SP41	7x7 PVC-coated	WD-40 Silicone	9	30	9	4.7	52.2%
15	SP41	7x7 PVC-coated	WD-40 Silicone	25	5	25	15.5	62.0%
16	SP41	7x7 PVC-coated	WD-40 Silicone	25	30	25	15.5	62.0%
17	PTFE	7x7	No Lubricant	9	5	9	3.7	41.1%
18	PTFE	7x7	No Lubricant	9	30	9	5	55.6%
19	PTFE	7x7	No Lubricant	25	5	25	10.9	43.6%
20	PTFE	7x7	No Lubricant	25	30	25	13	52.0%
21	PTFE	7x7	WD-40 Silicone	9	5	9	4.4	48.9%
22	PTFE	7x7	WD-40 Silicone	9	30	9	4	44.4%
23	PTFE	7x7	WD-40 Silicone	25	5	25	12.2	48.8%
24	PTFE	7x7	WD-40 Silicone	25	30	25	11.4	45.6%
25	PTFE	7x7 PVC-coated	No Lubricant	9	5	9	0	0.0%
26	PTFE	7x7 PVC-coated	No Lubricant	9	30	9	3	33.3%
27	PTFE	7x7 PVC-coated	No Lubricant	25	5	25	0.9	3.6%
28	PTFE	7x7 PVC-coated	No Lubricant	25	30	25	5.8	23.2%
29	PTFE	7x7 PVC-coated	WD-40 Silicone	9	5	9	1.2	13.3%
30	PTFE	7x7 PVC-coated	WD-40 Silicone	9	30	9	2.2	24.4%
31	PTFE	7x7 PVC-coated	WD-40 Silicone	25	5	25	5.8	23.2%
32	PTFE	7x7 PVC-coated	WD-40 Silicone	25	30	25	8.8	35.2%

Fig. 5 showed the main effects of the five input variables on force transmission efficiency. It was observed that the selection of material of sheath to Shimano SP41 and actuation cable to uncoated cable had the most significant positive effects on force transmission efficiency with improvement of 23% and 18%, respectively. Conversely, force transmission efficiency decreased by 5% with the increment of cable speed from 5mm/s to 30mm/s. As for cable pre-tension, the increment from 9N to 25N, produced a negative effect on the force transmission efficiency, although it was a very marginal decrease of 1%. As for the effect of the lubricant on force transmission efficiency using the Shimano SP41 and the PTFE tubes, adding lubricant on the later lead to an increment of force transmission efficiency by 2%, while for the former, addition of lubricant led to the reduction in the force transmission efficiency by 2%. While this observation seemed counter-intuitive, a possible reason for this was later found to be that the SP41, was by default, been pre-lubricated with a special silicone grease. Hence, the addition of the silicone degraded the original layer. However, as expected, adding silicone on PTFE tube had a positive effect on the force transmission efficiency with 2% increment.

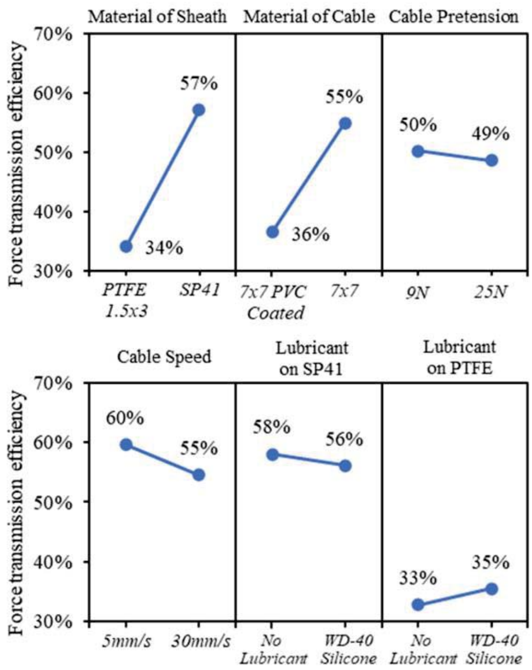

Fig. 5 Main effects of variables on force transmission efficiency

In summary, in order to enhance the actuation force transmission in tethering lines, it would be recommended to utilize lubricated sheaths and with operating conditions that have lower cable pretension and cable speed.

5. Conclusion

This study reported a 2^5 full factorial design of experiment to identify relevant and dominant design variables (material of sheath, material of actuation cable, type of lubricant used to coat the sheath, the cable pretension and the cable speed) for force transmission efficiency enhancement. Based on an experimental test-bed that compared the cable tension readings, before and after, passing through the tethering line, the conclusion indicated that the use of SP41 Bowden sheath and an uncoated steel cable are the most significant input variables which improved the force transmission efficiency by 22% and 18%, respectively. Reducing the cable pretension from 25N to 9N and reducing the cable speed from 30mm/s to 5mm/s improved the force transmission efficiency by 1% and 5%, respectively. While addition of lubricant in the Shimano SP41 sheath led to a negative effect because by default, it had been pre-lubricated with a special silicone grease and hence the addition of silicone degraded the default layer but, as intuitively expected, addition of silicone lubricant in PTFE tube had a positive effect on the force transmission efficiency. These results facilitated in the design of tethering lines with higher actuation force efficiency, and future work will explore the effect of other design explorations such as having multiple cables in a single sheath, as well as the different bending configurations of the tethering line when operating the entire manipulator and aerial drone system on-site.

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