Robotica (2015) volume 33, pp. 974–985. © Cambridge University Press 2014
doi:10.1017/S0263574714000721

Cable motion capture and analysis based on optical tracking system

Jingguo Ge* and Hao Gu

ABB Research Center-Mechatronics, Shanghai, postcode201319, China

(Accepted February 20, 2014. First published online: March 24, 2014)

SUMMARY
As a fatigable part of industrial products, cable is a valuable research topic to predict the product lifetime. Since the cable fatigue is related to the bending radius in motion, this paper presents a cable motion capture and bending radius calculation method based on optical tracking system. In particular, a marker sorting algorithm is developed for further spline interpolation in cable motion tracking. The cable bending radius calculation precision is analysed as well. The Results show that the proposed method can successfully track cable motion with an acceptable error for cable lifetime prediction.

KEYWORDS: Motion capture; Optical tracking; Cables; Industrial robots.

1. Introduction

Cables are widely used in electrical or electronic devices, and they are fatigable parts which can significantly affect the device life time. For example, industrial robots are usually attached with cables, as shown in Fig. 1. The cable moving with robot will be twisted, bended, or suffered by friction. So it is easy to be worn.

Thus it is a valuable research topic for cable fatigue life time prediction, because:

- it can decrease customer lost by alarming them in advance,
- it can save material of cable,
- it can provide guideline for a better cable layout design.

On the other hand, cables are very complex, since they are flexible, made of compound material (such as copper, steel, aluminum, rubber, plastic and so on), with different section shape (straight/twisted, naked/armored, single strand/multi strands). The materials properties and mechanical properties vary violently between different types, and new cable products with new structure emerge rapidly. So, it cannot be treated as simple flexible body. Furthermore, The S-N curve (a graph of the magnitude of a cyclical stress S against the logarithmic scale of cycles to failure N, which is a material property) shows that a little change of stress can cause a great change of life time. For a moving cable attached on robot, the stress level is relatively low, its fatigue type belongs to HCF (High Cycle Fatigue), and the lifetime is much more sensitive to stress level. A 30% error of life time prediction maybe needs the stress error less than 3%. So to predict the lifetime precisely, the stress value must be more precise.

Therefore, cable is a very complex and critical topic which attracts scholars in the world strives for few decades from different points of view with different methods. Basic knowledge and theory are summarized by Irvine,[1,2] linear dynamic of cables are reviewed by Triantafyllou,[3,4] nonlinear modeling, analysis and phenomena are comprehensively addressed by Rega.[5,6]

Yuefang Wang developed a closed-form solution for inextensible, 2D, traveling, sagged cables with nonlinear geometrical constraints and obtained dynamic configurations of inextensible cable.[7] Lucia Faravelli, *et al*. explored the applicability of non-linear state observation to cable dynamics.[8] Jens-Uwe Thalheim described a closed-loop and consistent methodology based on continuum

* Corresponding author. E-mail: Jingguo.ge@cn.abb.com

Fig. 1. An arc welding cable package fixed on an industrial robot.

mechanics in order to describe the kinetic stability of spaciously oscillating cables in different arrangements.[9]

Although it is not easy to model a cable mathematically, it is known that the material fatigue lifetime is related to the cyclical stress and the stress is related to the cable bending radius directly. The cable fatigue life time can be predicted with the stress history data according to accumulated damage theory. So for a cable fixed on a repeatedly running robot, if the cable's motion can be logged then its bending radius can be calculated. As a result, it is possible to predict cable fatigue life time with the existed accumulated damage theory.

Optical tracking systems are well known in gaming and movie industry to capture the human motion. Some high speed commercial optical tracking systems can track dozens of dynamic markers. But more low speed systems cannot theoretically, they can only log a lot of markers position with no order. The optical tracking system in this paper is a low speed system, which advantage is cheap, so the first problem for this paper is to track and sort markers for the interpolation process in cable motion tracking.

This paper presents a cable motion tracking and analysis method with a low-cost optical tracking system. In particular, a marker sorting algorithm is being developed and cable bending radius measuring precision is analyzed.

2. Experimental Platform Setup

The experiment system for cable motion tracking mainly includes a flexible cable, a robot system, a PC, an IPC, an optical tracking system, an Ethernet switch and some tailored mechanical parts to support the cameras and the cable, as shown in Fig. 2. In this system, the robot is used to run a preprogrammed path repeatedly. The cable with a lot of markers attached on it is placed in the center of the cell. One end of the cable is fixed on a pole, while the other end is hold by the robot. The optical tracking system is the OptiTrack system by NaturalPoint, whose Tracking Tools software is used to track the motion of cable, log and send the coordinates data of those markers. Four cameras are placed around the robot and the pole. The Ethernet switch is used to connect the PC and the robot controller together to transfer data between them.

Figure 3 shows the block diagram of this system, where all the devices are interconnected through an Ethernet switch. The IPC controls 4 cameras directly. The PC is used to control the IPC and the robot controller.

Frame rate is a very important performance index for the optical tracking system. It must be selected according to the moving speed of the being tracked object and the tracking accuracy. In this paper, the industrial robot TCP (Tool Center Point) speed is assumed at 500mm/s. The speed of an arbitrary point on the robot body could probably be two times of TCP speed (i.e. 1000mm/s). For a tracking accuracy of 10mm, the required frame rate should be 1000(mm/s) / 10mm = 100frame/s. So the lowest frame rate is 100fps.

Fig. 2. Experimental setup in lab.

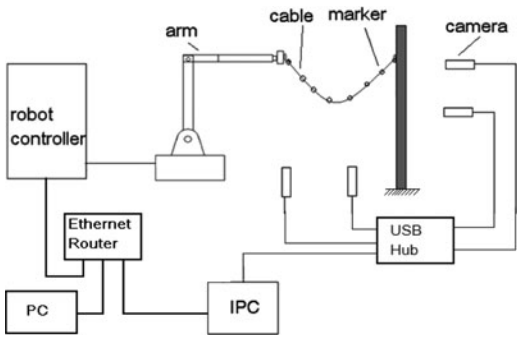


Fig. 3. Block diagram of the experimental setup.

The cell space is determined by the total area of cameras view field and the robot motion range. Before motion tracking experiment, the object to be tracked must be put in the common view field of all cameras view field to make sure that the object can be seen by as many as possible cameras.

3. Cable Motion Tracking and Processing

Simplest test cases are designed firstly, because they are easy to measure and validate, Based on the simplest cases, increase the complexity of the test step by step in the future. So the experiment is start from low speed and linear waving motion of cable.

For the designed cases, the experiments are carried out according to the steps in below.

(1) Calibrate the optical tracking system with the calibration wand & the calibration square.
(2) Prepare markers: attach some markers on the flexible body and track its motion by an optical tracking system.
(3) Run robot with preprogrammed path repeatedly.
(4) Record data when cable moving.
(5) Preprocess data: sort the 3D coordinates data of markers according to their space relationship.
(6) Calculate bending radius/curvature: calculate the bending curvature of the flexible body.

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press

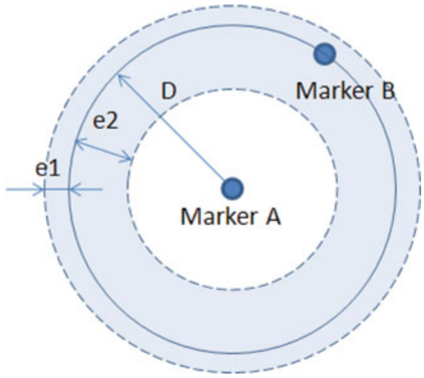


Fig. 4. The distance variation between two markers.

3.1. Marker preparation and data acquisition

In this step, the 3D coordinate data of those markers were acquired through optical tracking system. But before that, some preparation needs to be done. The requirement to place markers is as follows:

Put some marker(s) in the view field, it can be one static marker, or a trackable (defined by at least 3 markers with fixed space relationship, usually these markers are locate on a rigid body), which can be easily identified.

Put some more markers on the flexible body, the distance between these markers is known or fixed. Record their distance between each other, these conditions will be used in the later sorting algorithm.

After prepare according the above settings, then use the optical tracking system to tracking the movement of the flexible body and acquire the 3D coordinate data of all the markers on the cable. The data will be recorded as data file or broadcast through Ethernet.

In this paper, about 10 markers were attached on the cable (distributed evenly or with known distance) when using the optical tracking system to capture the cable's movement. The markers' 3D positions were captured with infrared camera and their positions are extracted by the optical tracking system. These 3D coordinates are recorded in a .csv (comma separated value) file.

3.2. Marker sorting algorithm and cable curve interpolation

The optical tracking system treats these markers as ideal space points with only position information. The optical tracking system can get the 3D coordinates of all the markers from one single frame, but the problem is it cannot log the coordinates of these markers with the same sequence, or identify them with a unique ID between different frames because of the low frame rate of the system. The coordinate data of these markers are only recorded in a line one by one.

So the first reason of preprocess is the sequence of these markers among lines is different. Before analysis the cable motion, i.e., the time sequence of these markers position, these markers must be identified or sorted. The second reason is that the optical tracking system can always make some wrong detections: (1) Missed markers. Some marker maybe hidden when the cable moved to somewhere or twisted, this can cause missing markers in the logged data file. (2) Fake markers. Some material in the view field can reflect infrared light, which will cause fake markers being logged by the optical tracking system.

The goal of preprocess is to find correct coordinates of each marker along the cable between two adjacent frames from the logged data file, which includes removing fake markers and sorting markers.

This work is done on VS2010 platform with C# language. The data preprocess can be separated into two cases, one is the case include only markers, another is include one or more trackables defined.

For the first case, the data format is simple, a marker is fixed in space for the purpose of positioning the cable, based on this marker, and then the other markers can be got in sequence according to their known distance. Figure 4 illustrates the marker distance change. Suppose two markers A and B on the flexible body, their original distance is D. When the flexible body moving, the distance between them will change, marker B will locate in a cirque area D^{+e1}_{-e2} around A. $e1$ is the distance increment caused by stretching, which related to the force applied to it, its value can be calculated according to hook's law and the cables equivalent elasticity. $e2$ is distance decrement caused by bending and

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press

twisting, it can be estimated by the moving speed and the equivalent material elasticity of the flexible body.

The algorithm to sort markers is described as below:

(1) Scan the data file (only several lines at the beginning of the data file, e.g., 10 lines), parse the data into 3D points and find the static marker.
(2) Rescan the data file from the beginning. For one valid data line, find the adjacent point to the static marker according to the predefined distance of each marker and consider its distance change. Find the markers one by one and output their 3D coordinates to a new file.

For the second case, the data format is a little bit complex. The algorithm is described as below.

(1) Scan the data file (several lines in the beginning), find the markers on the defined trackable (the rigidbody defined with several markers)
(2) Exclude the markers on trackable from the data line of markers
(3) Find the CoG(center of gravity) of the trackable
(4) Use the CoG as base, use the above algorithm without trackable to find marker one by one in the same line and output to a new file.

Since there are limited optical markers on the testing cable, data interpolation is required to reproduce a smooth cable with denser point positions. Least square method is the best choice to fit a curve, but its problem is it needs to know the function or curve type before fitting. In this paper, a general way is needed to fit the cable without known the cable's shape function. So the spline interpolation is chosen in this paper. Cubic spline interpolation is widely used in engineering applications, because of its continuous second derivation. The Cartesian cable data can be considered as the function of the marker position along the cable length s as

$$\begin{aligned} x &= f_x(s) \\ y &= f_y(s) \\ z &= f_z(s) \end{aligned} \tag{1}$$

For discrete markers s = 0, D, 2D, ... , (k−1)D, where k represents the number of markers. Via spline interpolation, piecewise cubic polynomial functions $f_x(s)$, $f_y(y)$, $f_z(s)$ with respect to cable length s can be obtained.

Consequently, the curvature can be calculated as

$$C = [(z''y' - y''z')^2 + (x''z' - z''x')^2 + (y''x' - x''y')^2]^{0.5}/(x'^2 + y'^2 + z'^2)^{1.5} \tag{2}$$

Where the prime denotes differentiation with respect to cable length s. The bending radius is the reciprocal of the curvature.

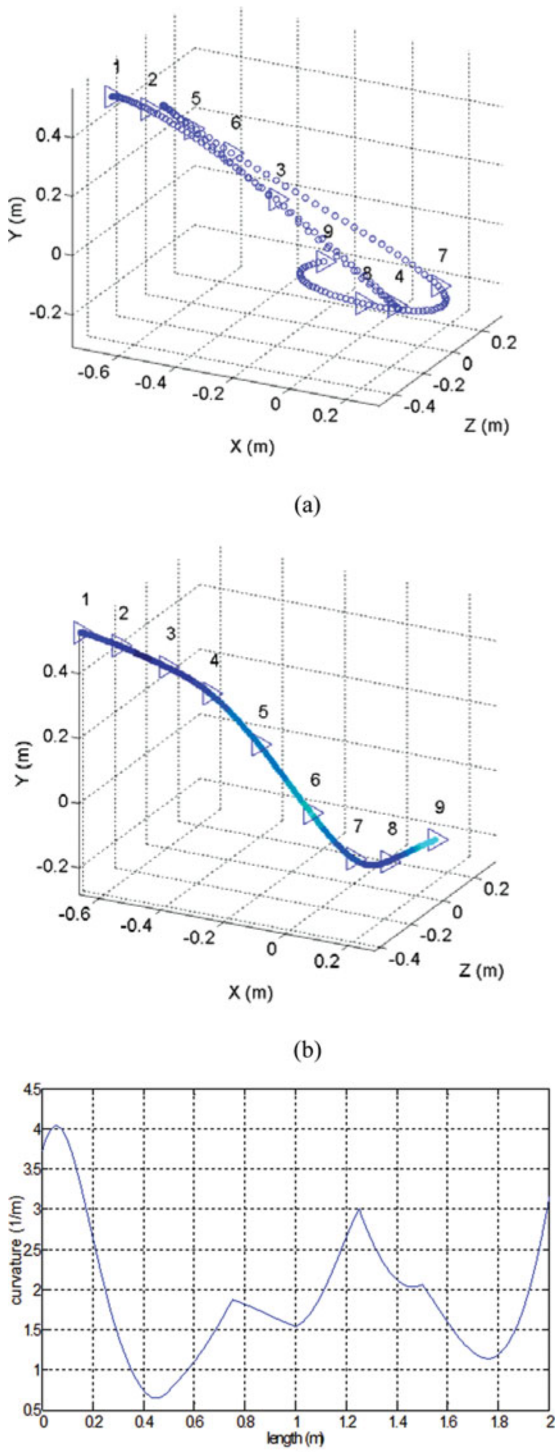
Detecting bending radius of the cable can be useful for further analysis on cable life time because internal stress value of a cable can be deduced from the bending.

Figure 5 is the result of preprocess: (a) shows the interpolated cable curve in a specified time before sorting, (b) is the curve after sorting according to the above algorithm, (c) shows the calculated curvature along the cable length.

4. Error Analysis

The presented cable motion tracking and its bending radius calculation are based on the spline interpolation, which can be general for adapting random cable poses during robot motion. However, the interpolated cable curve is not exactly the real cable curve, so there must be an error of the calculated bending radius. In addition, the optical tracking system itself can also introduce error.

In order to analyze the error of the proposed cable tracking and bend radius calculation, two typical planar curves have been studied:



(c)

Fig. 5. The marker sorting result of a cable tracking: (a) Before sorting markers; (b) After sorting markers; (c) The calculated curvature.

– A circle, which can be presented as

$$x^2 + y^2 = r^2 \tag{3}$$

– A catenary, which can be presented as

$$y = a \cosh(x/a) \tag{4}$$

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press

(a)

(b)

Fig. 6. Typical curve tracking test for error analysis: (a) a circle with 8 markers; (b) a catenary with 12 markers.

In particular, the catenary is usually known as a description equation for a hanging cable.[10] As illustrated in Fig. 6, a circle with r = 0.4m and a catenary with a = 0.5m have been setup in lab. Therefore, the ideal bending radius of the circle is a constant with $R_{\text{circle}} = r$, while the ideal bending radius of the catenary can be calculated as

$$R_{\text{catenary}} = a + (s - L/2)^{2/a} \tag{5}$$

Where L is the total cable length, which is 2m for the catenary in the lab setup.

By picking the passing points (x_i, y_i), $i = 1, 2, \ldots k$, along the ideal curve with the same number as the markers, the spline interpolation and bending radius can be proceeded. Thus, the bending radius error caused purely by spline interpolation can be obtained as shown in Figs. 7 and 8.

In particular, as shown in Fig. 7(a), the bending radius of the interpolated circle waves around the ideal radius along the curve length. As shown in Fig. 7(b), the maximum error is around 15%, which appears on the ends of the curve.

As shown in Fig. 8(a), the bending radius of the interpolated catenary fits the ideal radius along the curve length, except the two ends area. As shown in Fig. 8(b), the maximum error is around 10%. In fact, the radius error of interpolation curve can be reduced by increasing the interpolation points.

The bending radius error results with position data from the proposed tracking method are shown in Figs. 9 and 10. In general, the tracked radius has a similar behaves as the pure interpolation radius. As shown in Fig. 9(a), the tracked circle radius waves around the ideal radius. As shown in Fig. 10(a), the tracked catenary radius fits well in the middle part of the curve.

As shown in Figs. 9(b), and 10(b), the maximum tracking error is much bigger than the pure interpolation error. It is mainly caused by the marker placing and optical tracking system.

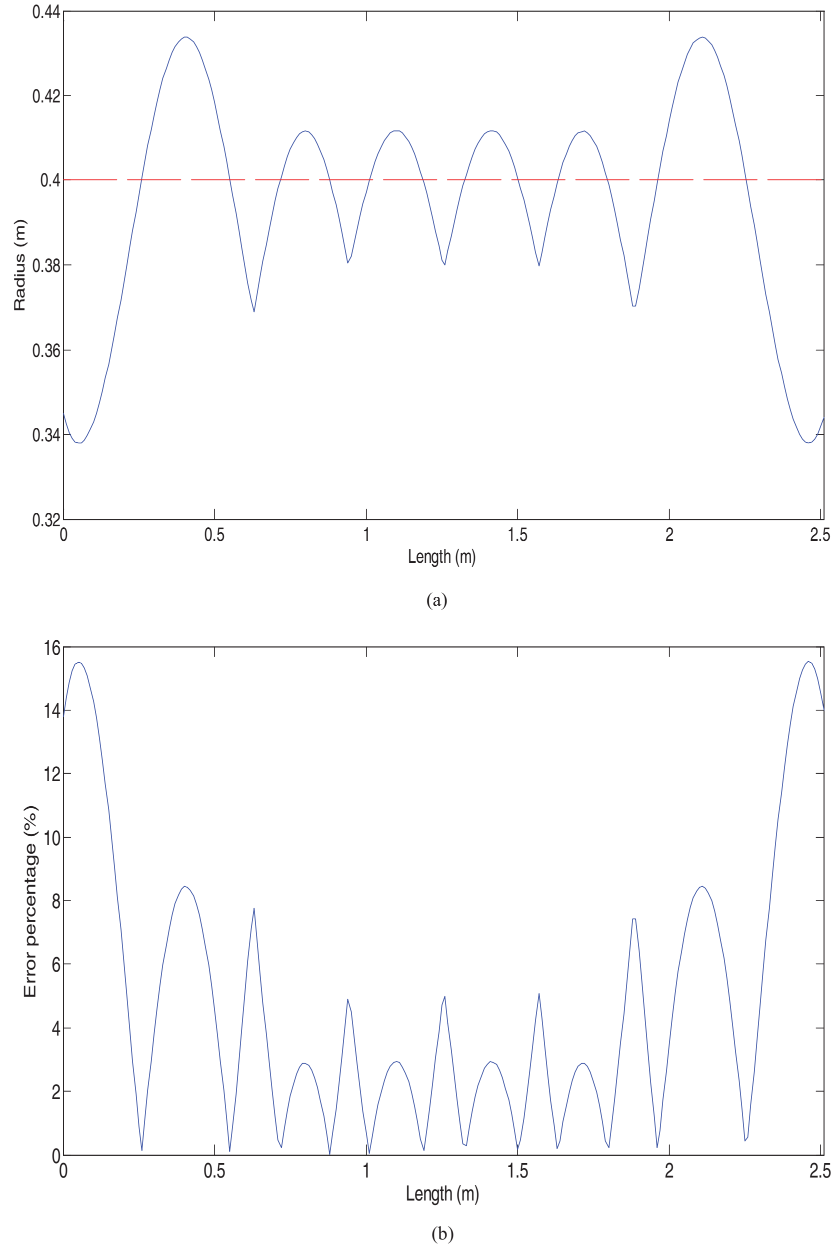


Fig. 7. Bending radius error between ideal circle and interpolated circle: (a) bending radius; (b) error percentage.

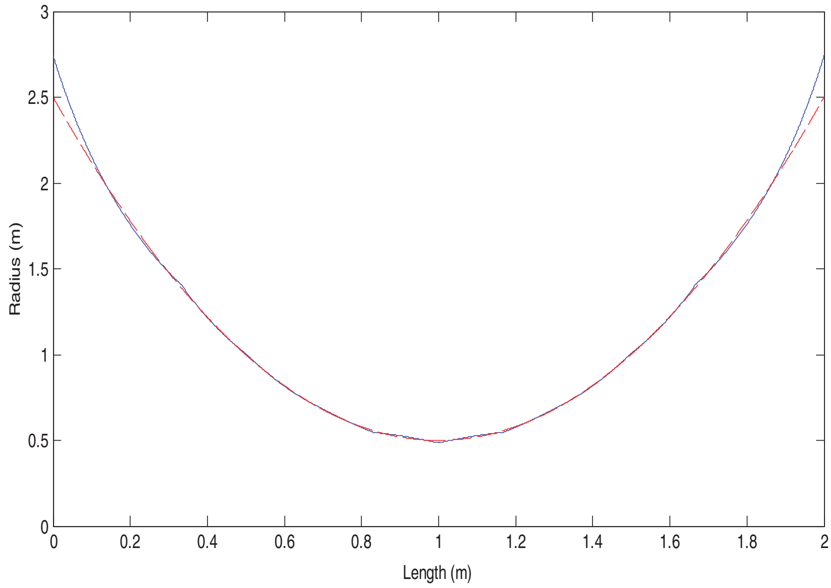
5. Future Work & Discussions

In the future, this result can be used to validate and to calibrate the computer simulation result. Furthermore, the final goal is to predict cable fatigue life time by only simulation without hardware test bench. This would speed up the cable lifetime estimation greatly. It can save time for cable life time estimation from one year to hours.

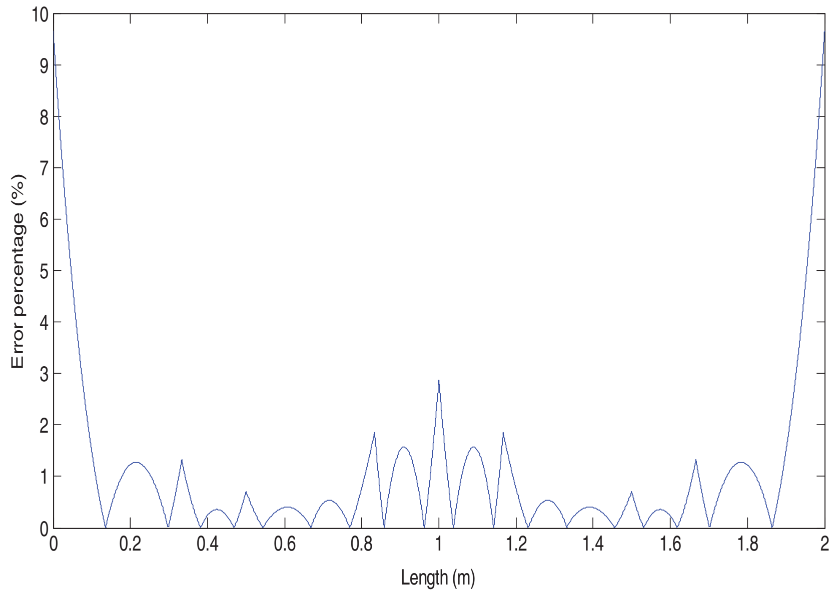
In details, the future work includes:

- Simulate cable motion in computer with physics engine.
- Calibrate the coordinate of optical tracking system and transfer coordinates.
- Calibrate the computer simulation result with this result.
- Adjust physics engine model according to the comparison result.

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press



(a)



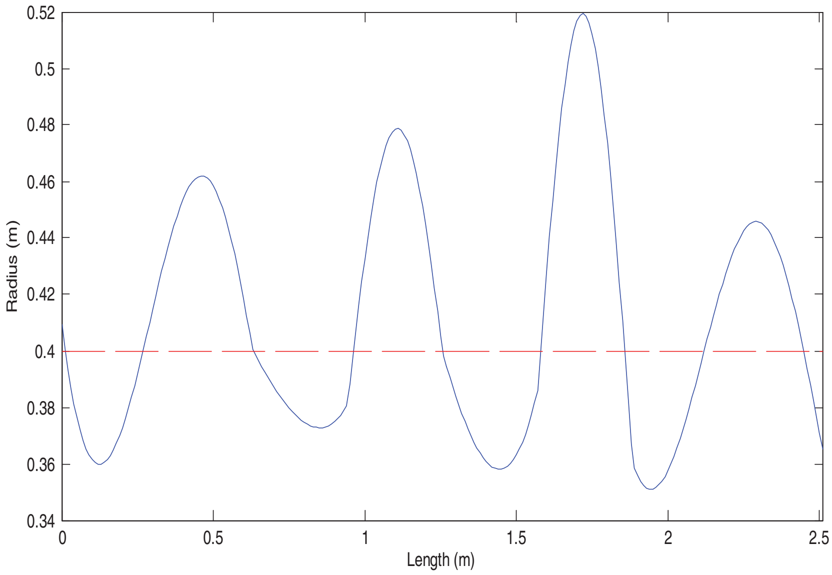
(b)

Fig. 8. Bending radius error between ideal catenary and interpolated catenary: (a) bending radius; (b) error percentage.

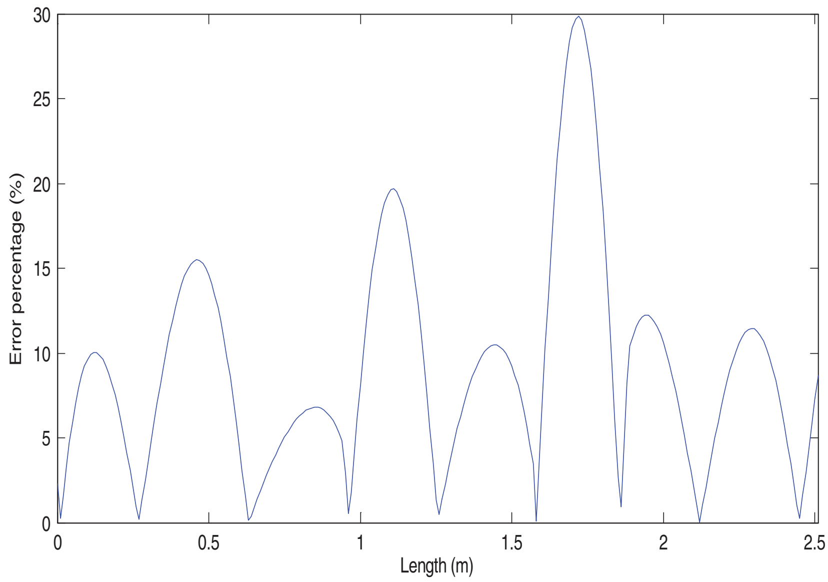
- Iteratively do compare and optimize the physics engine model to find the optimal result that a physics engine can reach.
- According to the precision of the physics engine simulation can reach, gives a clear evaluation result. Discuss whether the result is feasible to be calibrate/revise, whether is it possible to be used to predict cable fatigue life time.
- If the result of simulation is feasible to be calibrated, log the data history, and calculate the internal stress, estimate the lifetime according to the accumulated damage theory.

After cable motion is captured and fitted, it can be used to calibrate the computer simulation result. The error of cable motion captured by optical tracking system and computer simulation as illustrated in Fig. 11.

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press



(a)



(b)

Fig. 9. Bending radius error between ideal circle and tracked circle: (a) bending radius; (b) error percentage.

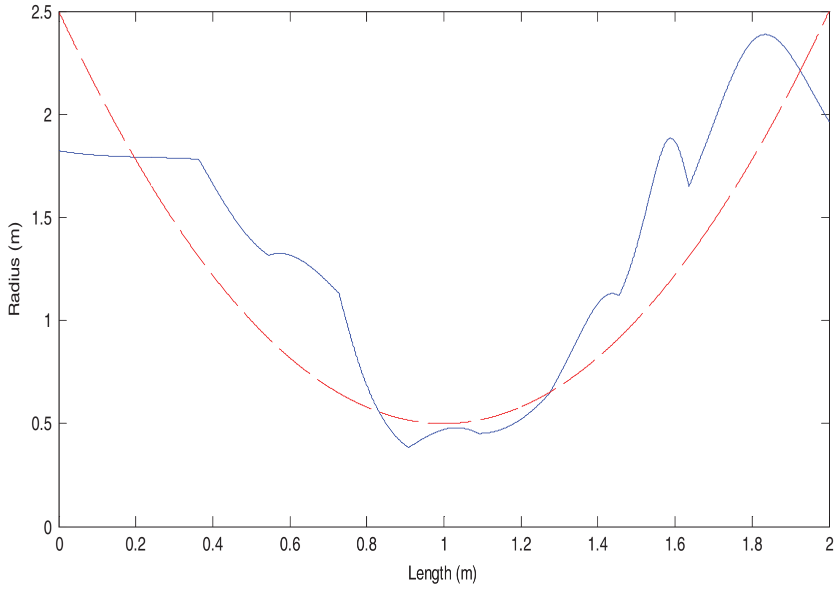
The error function can be defined as:

$$e^2 = \frac{\int_{t=0}^{T} \int_{s=0}^{L} (x_1(s,t) - x_2(s,t))^2 \, ds dt}{L \times T} \tag{6}$$

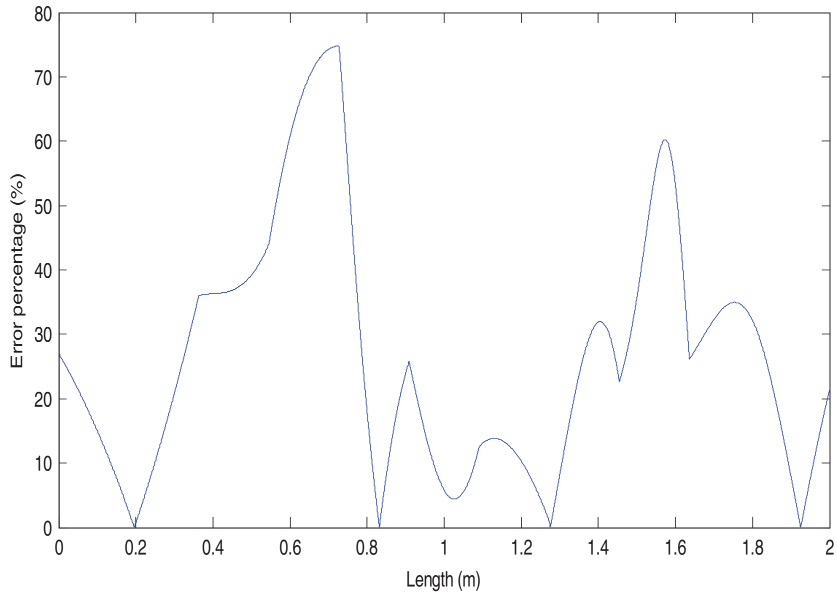
Where, L is the length of the cable, T is the total running time. s is the position in the cable. $x_1(s, t)$ and $x_2(s, t)$ is two results from RS simulation, tracking system (or analytical equation)separately.

To improve the motion capturing accuracy of a moving cable, a high speed optical tracking system is needed.

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press



(a)



(b)

Fig. 10. Bending radius error between ideal catenary and tracked catenary: (a) bending radius; (b) error percentage.

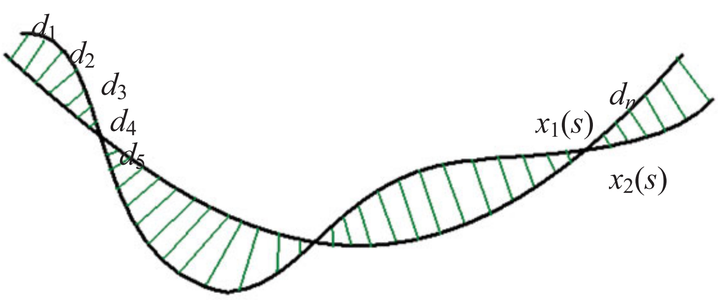


Fig. 11. Illustration of Cable motion error.

https://doi.org/10.1017/S0263574714000721 Published online by Cambridge University Press

6. Conclusion

In this paper, the optical tracking system is used in cable motion tracking, the cable motion data is acquired and a preprocessing algorithm of sorting markers is developed to find correct sequence of markers among sequence frames. Based on the preprocessing algorithm, a cable bending radius measurement method is presented. This work provides the base for further research in cable lifetime prediction.

References

1. H. M. Irvine, *Cable Structures* (MIT Press, Cambridge, MA, 1981).
2. H. M. Irvine and T. K. Caughey, "The Linear Theory of Free Vibrations of a Suspended Cable," *Proceedings of the Royal Society London*, A341 (1974) pp. 299–315.
3. M. S. Triantafyllou, "Linear dynamics of cables and chains," *Shock Vib. Dig.* **16**, 9–17 (1984).
4. M. S. Triantafyllou, "Dynamics of cables and chains," *Shock Vib. Dig.* **19**, 3–5 (1987).
5. G. Rega, R. Alaggio and F. Benedettini, "Experimental investigation of the nonlinear response of a hanging cable. Part I: Local analysis," *Nonlinear Dyn.* **14**, 89–117 (1997).
6. G. Rega, "Nonlinear dynamics of suspended cables, Part I: Modeling and analysis; Part II: Deterministic phenomena," *ASME Appl. Mech. Rev.* **57**, 443–514 (2004).
7. Y. Wang and A. C. J. Luo, "Dynamics of Traveling Inextensible Cables," *Commun. Nonlinear Sci. Numer. Simul.* **9**, 531–542 (2004).
8. L. Faravelli and F. Ubertini, "Nonlinear State observation of Cable Dynamics," *J. Vib. Control* **15**(7), 1049–1077 (2009).
9. J. U. Thalheim, *Nichtlineare Seilschwingungen und Stabilitatsanalysen fur Seilbewegungen* (Universitat der Bundeswehr Munchen Neubiberg, Nov. 2003).
10. Wikipedia. Catenary, (2012) Available http://en.wikipedia.org/wiki/Catenary.