State algorithm and double optimization design of safety cable retractor for gecko climbing robot

Lizhi Gu¹, Shanping Gao ¹, Jinling Song²*, Jianmin Xu ³, Junyan Xiao¹, Helu Chen¹ and Chenglong Liang¹

¹ Key Laboratory of Virtual Manufacturing Technology of Fujian Universities, Quanzhou University of Information Engineering, No. 249, Bodong road, Fengze District, Quanzhou city, Fujian province, China, 362000
² Quanzhou Normal University, No.398 Donghai Street, Fengze District, Quanzhou, Fujian Province, China, 362000
³ Xiamen Institute of Science and Technology, No. 600, Ligong road, Jimei District, Xiamen, Fujian, China, 361024
⁴ College of Mechanical Engineering and Automation, Huaqiao University, 668# Jimei Avenue, Jimei District, Xiamen, Fujian, China, 361021

* Corresponding Author,sjl3969@163.com.

Abstract. Gecko climbing robot cable is the core part of the robot system, which plays an important role in the basic life support of the operator. Based on the analysis of the function and performance requirements of the safety cable in the climbing process, the modular design scheme of the retractor is proposed according to the system engineering principle and optimization method, and the system is divided into retractor module, guidance and control module and mechanical structure module. Based on the analysis of the characteristics of the operator's safety state during the climbing operation, the operator's safety state set, the operator's safety state set and the operator's safety state set are formed. The whole process/full state algorithm is proposed. In the structural design, the basic functions of the retractor are divided into retractor module, guidance and control module and mechanical structure module. Considering the limited space and bearing capacity of the robot vehicle, on the premise of ensuring the safety and reliability, the lightweight optimization design is carried out to realize the function module and the double-pawl-bidirectional backstop-double-optimization retraction and release system with the most concise connection of each function module.

1. Introduction

In 2014, the total length of transmission lines in China will increase to 1.59 million kilometers by 2020, among which the lines of 220kV and above are 688,000 kilometers long. According to the current file distance L=400m, 1.72 million towers should be set. At present, for the maintenance of tower connection of high-voltage, ultra-high voltage and ultra-high voltage transmission lines (insulator condition, cable connection, splint condition, etc., as well as repair), the tower end is manually climbed to 10-tens of meters for corresponding operation, and then climbed down to the ground after the completion of the operation. This kind of work not only has the high request to the operator's business level, but also to their physical and mental condition challenges; more seriously, in the climbing process, in the maintenance process, once the operator error or physical and mental conditions appear abnormal, the operator is put in danger of life.
The design and use of safety cable has gone through two development stages: trial facility, generalization and specialization. In the climbing or moving robot field, several achievements have been gained. [1] Jaesung Oh at al. [1, 2] put forward autonomous laser toning system based on vision recognition and robot manipulator, and online path planning. Kapoutsis, A. C. at al. [3] created Plug-n-play Algorithm for Multi-robot Applications. Munzer, Thibaut at al. [4] developed preference learning on the execution of collaborative human-robot tasks. Song, Yalun at al.[5] provided a mechatronic approach for double robots in deburring of die casting. Virgili-Llop, Josep at al. [6] carried out a convex-programming-based guidance algorithm to capture a tumbling object. Ashkvari, Mahyar at al.[7,8] designed a 2-DOF ankle joint actuation mechanism for a humanoid robot, and for motor-tendon actuator for a soft starfish-like robot, respectively. Villagrossi, E. at al. [9] used single-point laser sensor in flexible robot-based cast iron deburring cell. Eslami, Mostafa at al. [10] presented a model of biped robot for Real-time Trajectory control. The current research arms at safety cable of the gecko climbing robot which plays a fatal role in the basic life support of the operator.

2. Design objectives and theoretical methods

By using the system engineering principle and optimization method from the overall layout and function module optimization design to the lightweight optimization design of each function module, the overall safety of the retractor is 100%, and each function module is light and reliable.

2.1. Analysis of working conditions

The safety cable can be connected with the fixer reliably, and it is convenient to lock and detach, so as to provide life security for the operator to carry the equipment on the upper and lower tower and safe operation. After the operator finishes the operation and returns to the ground with the help of the safety rope, the robot will take back the safety rope.

It is applicable to the standard transmission tower with a height of 50 meters or less.

2.2. Modular design principle and layout based on systems engineering principle

Due to field work, traffic inconvenience; micro-operation space is small. The reconditioning weight is limited, so in the overall design, the system engineering principle, reliability design and optimization method are used to implement the system function modularization to ensure the safety and reliability of the system operation. Meanwhile, the lightweight optimization design is carried out to reduce the reconditioning weight as much as possible so as to facilitate transportation, carrying and use. The basic functions of the retractor are divided into retractor module, guidance and control module and mechanical structure module. The basic functional modules are shown in figure 3.
3. Cable state algorithm

3.1. Division and mathematical expression of working condition stage of cable

Throughout the whole working process of climbing robot, the state of safety cable can be divided into 5 stages.

Stage A. Working preparation stage: the robot vehicle transceiver platform enters the working position —— it is firmly connected with the base, and electrified to start the system.

Stage B. Cable laying stage: the robot vehicle climbs to the tower end, releases the cable connector, and is fixed to the tower end rod. At this point, the tension $T$ of the safety cable gradually increases from zero to the dead weight of the tower length safety cable, $T_m$.

Stage C. Normal working stage of cable: the basic conditions are as follows, which can be divided into four sub-stages:

Sub-stage a, normal climbing: the connection between the cable and the operator should be safe, reliable and comfortable (in another way). If the operator climbs one step, the rope will bend and the tension of the cable will be reduced, but it will not be less than the tension caused by the dead weight of the rope. Sub-stage b, normal climb down: with each lower handle, the rope tension reaches a certain value and then decreases. Sub-stage c, abnormal climbing: the operator moves too fiercely and suddenly drops for the upper armrest, causing the tension to increase abruptly. Sub-stage d, abnormal in climbing down: the operator acts too violently and the tension increases suddenly; the operator loses control of the hand or foot, the body falls, and tension increases (safety cable, statically, state and gesture of the operator).

For safety reasons, at least 2 operators are supposed to be on site; each operator can control the robot remotely! The logical diagram of "robot stage—safety rope state (tension) — operator state" is shown in figure 4. with

$$\text{Set1}\{\text{stage1, stage2, stage3, stage4, stage5, stage6}\},$$
$$\text{Set2}\{\text{tension1, tension2, tension3, tension4, tension5, tension6}\},$$
$$\text{Set3}\{\text{state11, state22, state33, state44, state55, state66}\},$$

Stage D the recovery section of the cable with the carrier

Stage E. Post-processing section: the cable is locked in the vehicle, and the system is cut off; the robot system was unloaded from the base. Because of the situation in this stage, no relation with the operator’s life, the author no longer mentions Stage E thereafter.

Due to the bad operating environment and traffic inconvenience, the modular design of the robot system as well as the cable subsystem is also modular in layout and design.

3.2. Mathematical description and state algorithm of the working stage

Stage C is subdivided into 4 sub-stages, and the corresponding cable tension is expressed as follows:

Sub-stage a: the workers climbed up. At this time, the safety cable and the tower end are fixed, the robot vehicle's limbs and the handle are firmly grasped, and the safety cable is arranged along the frame on the rack. The operator fastens the safety belt and climb to the tower end smoothly. The initial tension of the safety cable is $T_m$, which is caused by the dead weight of the safety cable. During the climbing process, the operator occasionally experiences a slight drop. If the increase in cable tension caused by $\Delta b$ such a sudden drop is recorded as, then the tension in this sub-stage is

$$T_o = T_m + \Delta b$$

where $\Delta b$ is a variable, related to the climbing habits of transient operators, and can be described by the e exponent function or other appropriate function. The cable tension of this sub-stage is

$$T_m \leq T_o \leq T_m + \Delta b$$

The cable is in the state of "instantaneous multiple small releases - total gradual traction".

stage b: the operator climbed down. At this time, the safety cable and the tower end remain fixed, the robot vehicle's limbs and the handle are firmly clenched, and the safety cable is basically closed in the retractor.

$$T_o = T + \Delta b$$
where $T$ is a variable, the instantaneous tension caused by the self-weight of the safety cable is constantly released, and the maximum value is set when it reaches the ground, $T_{\text{max}} = T_m$.

$\Delta b$ is a variable related to the climbing habits of instantaneous operators. It can also be described by exponential function or other appropriate function.

The cable tension of this sub-stage is

$$0 \leq T_b \leq T_m + \Delta b$$

The cable is in the state of "instantaneous multiple small release - total gradual release".

Sub-stage c: the operator lost control during the climb. Either by mistake or because of physical discomfort, or for other reasons, the operator is out of the proper bearing relationship with the handle and falls into a free fall. At this time, the safety rope plays the role of safety guarantee. The initial tension of the safety rope is $T_m$.

$$T_c = T_m + T_g$$

where $T_g$ is a variable, and the tension of the cable increases abruptly due to the operator's fall. The increase of a large amount of tension can be described by exponential function or other appropriate function.

The cable tension of this sub-stage is

$$T_m \leq T_c \leq T_m + T_g$$

The cable is in "a large transient value of tension, bearing the operator's weight", and the reverse backstop works.

Sub-stage d: the operator lost control during the descent. The sudden increase in the tension of the cable caused by such a sudden fall into free fall is denoted as, then the tension of the cable in this sub-stage is denoted as

$$T_d = T_g + T_m$$

where $T_g$ is a variable, and the tension of the cable increases abruptly due to the operator's fall. The cable tension of this sub-stage is

$$0 \leq T_d \leq T_g + T_m$$

The cable is in "a large transient value of tension, bearing the operator's weight", the reverse backstop works. Operator status - cable tension - system operating stage are described in detail in matrix, see figure 6.

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**Figure 5. State-stage diagram**

**Figure 6. Status-tension-working stage matrix**
It means "normal operation", "terminal load", "abnormal operation" and "no operation", respectively, so that measures can be taken quickly.

4. Optimization principle of lightweight design

According to the structure function, the retractor can be divided into a frame, a sliding plate, a rotating shaft assembly, a guidance control device and a safety cable body. As one of the core parts of climbing robot, the safety cable retractor is on the robot vehicle, and the overall requirement is that the self-weight should be as light as possible on the basis of safety and reliability. The optimization design is carried out with the light weight as the objective function, the security and reliability as the constraint, and the basic size of the component unit of the retractor as the decision variable.

\[
\min W = \sum_{i=1}^{n} \lambda_i w_i(X)
\]

\[
s.t. \left\{ \begin{array}{l}
g_1(X) = c_1 \\
g_2(X) = c_2 \\
x \geq 0
\end{array} \right.
\]

What needs to be pointed out is that the unit quality of the retractor can be either a part or an assembly unit. In this paper, it refers to a functional module. When a functional module consists of multiple parts and lower level assembly units, quality needs to be further distributed and checked for compliance with safety and reliability requirements. The decision variable \(X\) is the quality characteristic parameter corresponding to the above-mentioned parts or assembly units. The design requirements can be met through repeated optimization and inspection. The overall design (schematic) is as follows.

![Figure 7. Layout of the retractable system with the main components](image)

5. Conclusions

Gecko climbing robot cable is the core part of the robot system, which plays an important role in the fatal support of life for the operator. The safety and reliability of its function and the smoothness of its movement have been guaranteed by systematically analyzes and design based on systems engineering and optimization methods. The due state of cable in the whole operation process was divided into four stages according to its proper function-tension characteristics, among which operation C stage is subdivided into four sub-stages for even more details of the state of operator-tension of the cable.
The matrix of operation stage-safety cable tension-operator state is developed and described in terms of the sets of numbers, from which the normal states and dangerous states were clearly depicted with the corresponding tensions of cable in sequence. The matrix may be used in better control of the operation, and even may be employed in prediction of danger for the operators, especially in Stage C.

According to the modular functional design and structural lightweight optimization design, the design scheme to meet the needs of the enterprise is given to ensure the smooth and reliable process. Due to the small space of the vehicle, the carrying capacity is greatly limited, the lightweight optimization design is carried out on the premise of ensuring the safety and functional reliability. Based on the principle of high reliability and lightweight optimization, the spatial arrangement of functional modules in the vehicle was proposed, and the above functions were realized by the most concise connection of the functional modules.

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References
[1] Jaesung O, Hyoin B, Jeongsoo L and Oh J H 2016 Development of Autonomous Laser Toning System Based on Vision Recognition and Robot Manipulator. Proc. of 2016 6th IEEE Int. Conf. on Biomedical Robotics and Mechatronics, June 26-29 Singapore
[2] Mirjalili R, Yousefi K A, Shirazi F A and Mansouri S 2016 Online Path Planning for SURENA III Humanoid Robot Using Model Predictive Control Scheme. Proc. of 4th RSI Int. Conf. on Robotics and Mechatronics, pp 416-21, October 26-28, 2016. Tehran, Iran
[3] Kapoutsis A C, Chatzichristofis S A and Kosmatopoulos E B 2019 A Distributed, Plug-n-play Algorithm for Multi-robot Applications with a Priori Non-Computable Objective functions. Int. Journal of Robotics Research, vol. 38 (7) : pp 813-32
[4] Munzer T, Toussaint M and Lopes M 2017 Preference learning on the execution of collaborative human-robot tasks. Proc. of IEEE Int. Conf. on Robotics and Automation, May 29 - June 3, 2017, Singapore, pp879-85
[5] Song Y L, Zhang G, Hou Z C, Wang WJ, Xu Z, Gu X, Han C S and Huang A Y 2017 A Mechatronic Approach for Double Robots Collaborative Deburring of Die Casting. Proc. of vSII 2017 - 2017 IEEE/SICE Int. Symposium on System Integration, December 11 - 14, 2017, Taipei, Taiwan, pp 614-19
[6] Virgili L J, Zagaris C, Zappulla R, Bradstreet A and Romano M 2018 A Convex-programming-based Guidance Algorithm to Capture a Tumbling Object on Orbit Using a Spacecraft Equipped with a Robotic Manipulator. Int. Journal of Robotics Research vol.38(1), pp40-72
[7] Ashkvari M, Yousefi Koma, Aghil K H, Shariat P M Design Improvement of a 2-DOF Ankle Joint Actuation Mechanism for a Humanoid Robot. Proc. of 4th RSI Int. Conf. on Robotics and Mechatronics, October 26-28, 2018, Tehran, Iran, pp349-44
[8] Munadi M, Ariyanto M, Setiawan J D, Purwanto E, Taufiqurohman A A M, Hasan F A, Settia S and Muhammad N Design and Manufacturing of Motor-Tendon Actuator for a Soft Starfish-Like Robot. Proc. of ISSIMM 2018 - 3rd Int. Seminar on Sensors, Instrumentation, Measurement and Metrology, December 4-5, Depok, Indonesia, pp54-7
[9] Villagrossi E, Cenati C, Pedrocchi N, Beschi M and Molinari T L. Flexible Robot-based Cast Iron Deburring Cell for Small Batch Production Using Single-point Laser Sensor. Int. Journal of Advanced Manufacturing Technology. vol. 92(1-4), 2017:pp 1425-38
[10] Eslami M, Yousefi K A and Khadiv M 2016 A Novel Three-mass Inverted Pendulum Model for Real-time Trajectory Generation of Biped Robots. Proc.of 4th RSI Int. Conf. on Robotics and Mechatronics, October 26-28, 2016, Tehran, Iran, pp 404-409