Model Checking The Robot Control System for Live Maintenance of Substation Equipment

*

Hongyi Wu, Zhuo Wang, Xiaoyu Qin, Kaihan Shen, Haolin Yang, Kai Zheng, Xin Huang
Department of Computer Science and Software Engineering
Xian Jiaotong-Liverpool University
Suzhou, China
{Hongyi.Wu16, Zhuo.Wang16, Xiaoyu.Qin16, Kaihan.Shen16, Haolin.Yang16, Kai.Zheng, Xin.Huang}@xjtlu.edu.cn

***Abstract*—For the purpose of improving the low efficiency of substation control system, the design of innovative robot control system for live maintenance has become a necessity. The paper gives a detailed explanation for the structure of this system from two different angles. Because of the demand of flexible control and the incidence of certain unstable factors, the reliability of performance of the system becomes quite significant. Therefore, this paper applies PRISM to implements probabilistic model checking for the system to decrease risks. Besides, the experimental results are expected to provide suggestions on how to improve the development of robot control system for maintenance. Based on result of multiple experiments, it is recommended to reduce failure rate of single module. Furthermore, for the planning modules, it will improve reliability of robot control system apparently from changing failure rate of once a month to three month. Therefore, improvement of planning module is essential for reducing failure rate of planning module. Safety module is also important for robot control system although experiment shows that it is difficult to distinguish effect of safety module. Advanced safety module will improve performance of robot control system.**

***Index Terms*—Robot control system; Maintenance; Model checking; PRISM; (Continous-Time Markov Chain) CTMC**

I. Introduction

In response to the accelerated development of society, high reliability, high power quality and high load density have been urgently needed by the power grid [1]. Stringent demand for energy outages has become a crucial issue that cannot be ignored anymore because of the decreasing number of opportunities for key lines. Therefore, in order to solve this tough issue, the implementation of advanced live repair operation technology is quite necessary.

Briefly defined as an advanced technology used for maintenance and repair operation [2], it will satisfy the urgent demand of the power grid. However, compared with the traditional technology, the characteristics of larger volume and weight, higher voltage and the station equipment intensive add pressure to the operation of live maintenance of substation equipment [3]. Besides, the low efficiency of the substation staff switching, the massive amount of labor costs and the growing incidence of power accident caused by inappropriate use are also significant factors needed to be considered when implementing [4]. Hence, in order to solve the issues above and to improve the situation, the service robot equipped with the robot technology has been applied. The working robot control system is designed to solve the low degree of automation of the substation robot, adopt- ing ROS(Robot operating system) as the communication and control framework, Beckhoff C6930 as the main controller,also including auxiliary sensor and actuator [5]. With such progressive technologies and device used, the system has the following advantages [6]:

- Particular motion controller with high accuracy;
- Hierarchical control to boost the efficiency;
- Efficient framework upgrading system logic.

Although the enormous value the system possesses, the verification of the reliability of the system is a challenge. In this paper, the reliability of the work robot control system is verified by the probabilistic model checking technology: PRISM. PRISM is an efficient and professional probabilistic model checker for system. The implementation of the experiments of verification uses the Continuous-time Markov chain (CTMC) which takes values in constrained state space [7].

- The results of model checking various components in the structure of the system help us find out the main elements influencing the whole system.
- The improvements of the new redesigned system is attributable to the experiment results.

The structure of this paper is as follows: Section II gives a brief introduction to the architecture of the system from two perspectives. Then, Section III makes a critical evaluation of the experiment results. Finally, the conclusion and further suggestions for the future are also given in the SectionIV.

II. Related Work

Some related researches have been introduced to design working robot control system, additionally, there are some supporting reports projected to verify the reliability of this system. They are revealed as follows: In [8], robot control system is used for search and rescue missions with the application of 3D

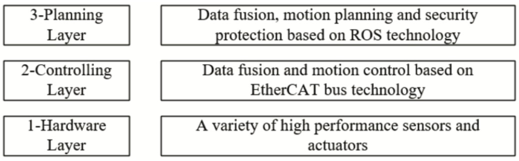

Fig. 1. Hierarchical structure of robot control system.

vision scheme. Different modules are distributed to handle the flexible data collected by sensors. Besides, the hierarchical architecture structure is also employed for the purpose of decision-making in autonomous mobile robot system, which is beneficial for the increase of the efficiency [9]. As for the reliability, Markov-based reliability model is suggested for the robot control system, it successfully provides detailed models checking of the transformer substation maintenance work robot system [10]. However, it failed to verify the reliability of the whole system. This paper will give analysis to the experiment results to check the reliability of the whole work robot control system for the maintenance of substation equipment.

III. FRAMEWORK

The architecture of the work robot control system can be interpreted from two angles: hierarchical structure and module structure separately. From the first perspective, the system adopts stratified design, including hardware layer, control layer and planning layer three layer structure [11]. The hardware layer integrates various high efficiency sensor and actuator; control layer is designed to ensure the effectiveness and real- time data acquisition and control with the application of EtherCAT bus technology; planning layer employing ROS technology contains data fusion, motion planning and security protection [12]. From the module structure of the system, based on the ROS control system, transformer substation maintenance work robot system functions as the control and communication framework [13]. The function module of the system is divided into the following components: motion planning modules, motion control modules, data fusion modules, security modules, laser processing modules, visual processing modules, laser data acquisition modules, data acquisition module and data bus vision acquisition modules [14]. Each function module composes the framework module and the framework module is the prerequisite for the stable operation of the function parts [15]. They influence and rely on each other in the whole module structure.

IV. MODELLING IN PRISM

PRISM is probabilistic model checking tool which can be capable to build and analyze different types of probabilistic models.

A. Introduction to CTMC

Continuous Markov chain(CTMC) is a stochastic model which can be used to evaluate the system stability. The

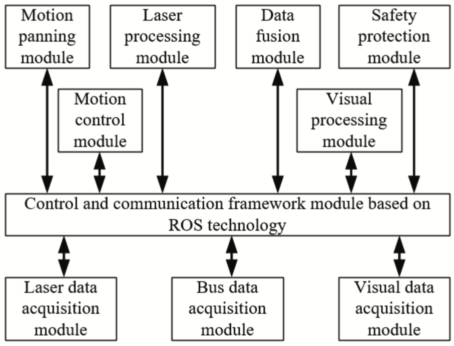

Fig. 2. Module structure of robot control system.

main feature of CTMC is that the probability of each event depends only on the state attained in the previous event. There is another type of Markov chain which is in discrete time (DTMC). The main difference between CTMC and DTMC is that DTMC can only remain in any state for one unit of time before transiting while CTMC can remain for many units of time. In robot control system for live maintenance for substation equipment, a state sometimes should be remained for more than one unit of time. CTMC can be used to simulate the process so that the probability of breaking down and expected breaking time period can be calculated.

B. Breaking down states

There are several situations which cause failure:

- Control and communication framework breaks down
- Any sensor and actuator in Hardware layer break down
- Any part in Controlling layer breaks down
- Any part in Planning layer except safety protection system breaks down

The malfunction of safety protection system cause the whole system failure. However, it will increase the failure rates of other modules. In the controlling layer, motion control and visual processing modules are possible to reboot when malfunction occurs.

C. Module Construction

There are five types of module in the robot control system for live maintenance for substation equipment : Framework modules, hardware modules, controlling modules, planning modules and safety protection modules.

SafeProtection Module: There is an insulated safety protection control system in this module. The possible states of this system is applicable or failed. Variable s represents safety protection control system. The variable value is 0 or 1.The failure rate of the system is lambda_1month which is 1/(30*24*60*60) which means the failure will occur once in a month. The state transition is expressed as:

$$[]s > 0- > s * lambda_1 month : (s = s - 1); \qquad (1)$$

This expression shows that if the safety system breaks down, the value of s will decrease by 1.

Framework Module: This module contains a control and communication framework based on ROS robot control system. Variable a represents framework and the value is 0 or 1.The failure rate of the framework is lambda_10y which is 1/(10*365*24*60*60) which means the failure will occur once in 10 years. The state transition is expressed as:

$$[]l > 0\&s > 0- > l * lambda_1y : (l = l - 1); \quad (2)$$

$$[]l > 0\&s = 0- > l * 2 * lambda_1y : (l = l - 1); \quad (3)$$

The second expression shows that the failure rate of framework will double if the safety module breaks down.

Hardware Module: This module contains three similar submodules and there is one sensor or actuator which collects laser, bus and visual data in each submodule. Variable l represents sensor and the value is 0 or 1.The failure rate of the framework is lambda_1y which is 1/(365*24*60*60) which means the failure will occur once in one years. The state transition is expressed as:

$$[]l > 0\&s > 0- > l * lambda_1y : (l = l - 1); \quad (4)$$

$$[]l > 0\&s = 0- > l * 2 * lambda_1y : (l = l - 1); \quad (5)$$

The second expression shows that the failure rate of framework will double if the safety module breaks down.

Controlling Module: This module contains two submodule: Motion Control module and Visual Processing module which are in charge of real-time data acquisition and control. They share the same mechanism which allows them to reboot when failure happens so that it is enough to take one of them as example. Variable m represents motion control module and the value is 0 or 1.The failure rate of the submodules is lambda_1y which is 1/(365*24*60*60) which means the failure will occur once in one years. The reboot rate is delta_r which his 1/30. The state transition is expressed as:

$$[]m > 0\&s > 0- > m * lambda_1y : (m = m - 1); \quad (6)$$

$$[]m > 0\&s = 0- > m * 2 * lambda_1y : (m = m - 1); \quad (7)$$

$$[reboot]m = 0- > delta_r : (m = 1); \quad (8)$$

The second expression shows that the failure rate of submodule will double if the safety module breaks down.The third expression indicates that the system has 1/30 possibility to reboot.

Planning Module: This module contains three systems which are in charge of motion panning, data fusion, and laser processing. Variable p represents motion panning system and the value is 0 or 1. The failure rate of the framework is lambda_1month which is 1/(30*24*60*60) which means the failure will occur once in one month. The state transition is expressed as:

$$[]p > 0\&s > 0- > p * lambda_1 month : (p = p - 1); \quad (9)$$

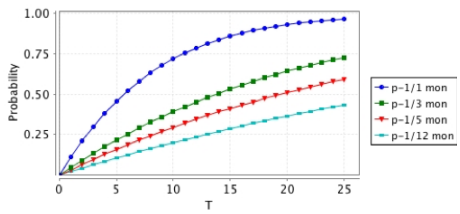

Fig. 3. the failure probability of robot control system in 25 days with various failure rates of planning modules.

$$[]p > 0\&s = 0- > p*2*lambda_1 month : (p = p-1); \quad (10)$$

The second expression shows that the failure rate of system will double if the safety module breaks down. The other two systems share the same expressions.

D. Validation

The whole system will break down when the number of system component is less than the minimum value. MIN_planning_Modules, MIN_controlling_Modules, MIN_hardware_Modules, and MIN_hardware_Modules refer to the minimum number of working system in planning module, data acquisition and control tool in controlling module, sensors and actuators in hardware module, and central framework. The following formula is to check the state of the whole system.

$$\begin{aligned} formuladown = &(p < MIN\_planning\_Modules)|(c < MIN\_planning\_Modules)| \\ &(f < MIN\_planning\_Modules)|(m < MIN\_controlling\_Modules)| \\ &(v < MIN\_controlling\_Modules)|(l < MIN\_hardware\_Modules)| \\ &(b < MIN\_hardware\_Modules)|(q < MIN\_hardware\_Modules)| \\ &(a < MIN\_framework\_Module) \end{aligned} \quad (11)$$

p, c, f refer to motion panning, laser processing, and data fusion tool in Planning module. m, v refer to motion control and visual processing system in Controlling module. l, b, q refer to laser data, bus data, visual data acquisition sensor or actuators in Hardware module. a refers to framework in Framework module. There is one property is used to show the failure rate resulting system shut within one day:

$$P = ?[trueU <= (T * 3600 * 24)down] \quad (12)$$

V. IMPACT

A. Impact of Planning Modules

The first stage in model checking is related to the planning modules. The different sets considered in this modules part is the failure rate.

As the figure shows, p-1/1 mon means that the failure of one of three modules occurs once a month.

Finding. There are several findings from verifying the impact of modules in the system. Finding. The decreasing failure rate of each module from planning modules reduces the failure possibility of the whole system, which means the failure of single planning module has great impact on the whole system.

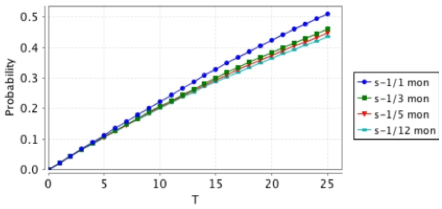

Fig. 4. the failure probability of robot control system in 25 days with various failure rates of safety protection module.

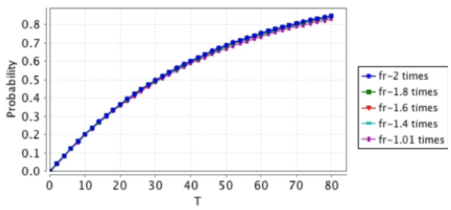

Fig. 5. the failure probability of robot control system in 80 days with various protection effect of safety protection module.

Finding. The lower failure rate of one planning module could enhance the system reliability apparently.

B. Impact of Safety Modules

The next set of experiments is to verify the effect of safety protection module.

fr-2 times means that when the module fails, failure probability of other modules of the system will double. The function of the safety protect module is to observe any other modules from some accidents. When the safety module fails, the failure probability of other modules of the system will increase. There are three findings from the two figures above.

Finding. The decreasing failure rate of safety protection modules reduces the failure possibility of the whole system. The lower failure rate of the module could enhance the system reliability.

Finding. Figure 4 shows that, when the failure rate of module is less than 1/3 months, the reliability tends to improve slight.

Finding.. The improvement of protection effect is slightly, since the diverse ideal condition, the failure of the module which causes 1.01 times change for the failure of other modules hardly distinguish from other condition, which means the with the intention of improving reliability of the system, it is considered to develop the protection effect substantially.

C. Impact of Motion control Module & Visual processing Module

The third set of experiments are performed in order to verify the effect of Motion control module and Visual processing module with their reboot rate on the whole system.

Finding. Figure 6 shows that the reliability of the whole system is corresponding to the duration of Motion control module and Visual processing module. The probability of system failure will approach 1.0 after 30 days. When the

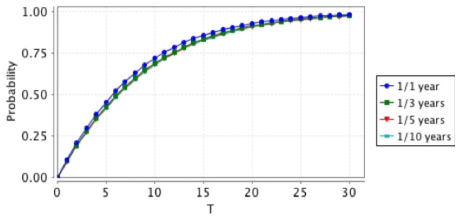

Fig. 6. the failure probability of robot control system in 30 days with various failure rates of Motion control module & Visual processing module.

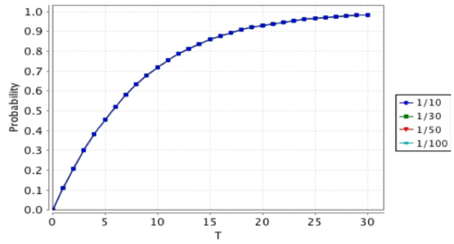

Fig. 7. the failure probability of robot control system in 30 days with diverse reboot rates of Motion control module & Visual processing module.

failure rate of Motion control and Visual processing modules is less than once three years, its impact on system reliability will be slightly.

Finding. Lower failure rates of modules lead to higher reliability of the whole system. However, the effect of Motion control module and Visual processing module on the whole system is not significant. In addition, Motion control module and Visual processing module have possibility of reboot which enable them to recover from the failure. The initial reboot rate is 1/30 which indicates the module could recover once in 30 times of failure. The aim of next set of experiments is to verify the effect of reboot rate on the system.

Finding.. Figure 7 demonstrates that there is almost no effect of reboot rate on the whole system since only the blue line is visible.

D. Impact of Data Acquisition Module

The Robot control system has three data acquisition modules. These modules are laser data acquisition module, bus data acquisition model and visual data acquisition model. These experiments are executed in order to verify the effect of data acquisition modules on the system.

Finding. Figure 8 represents that reliability of whole system is relative to data acquisition module. From five days to twenty days, the blue line has slight distinction with the green line. However, after 25 days, there is not too much difference between these two lines.

E. Impact of Control and Communication Framework Module

Experiments is performed to claim the relationship between reliability of robot system and control and communication framework module.

Finding. Figure 9 verifies effect of control and communication framework module on the whole system. It can be

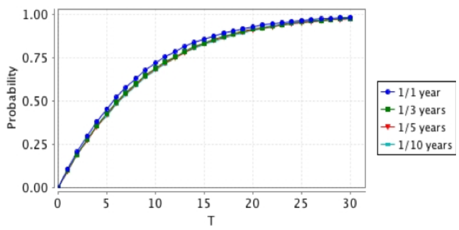

Fig. 8. the failure probability of robot control system in 30 days with various failure rates of data acquisition module.

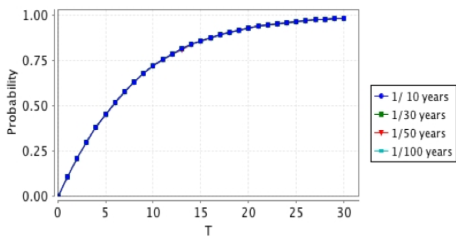

Fig. 9. the failure probability of robot control system in 30 days with various failure rates of control and communication framework module.

concluded from figure that different failure rates of control and communication framework module will not have effect on reliability of robot control system

VI. RECOMMENDATION

From the findings we conclude, there are several recommendations for improving the reliability of the robot control system.

- As the lower failure rate of single module reduces enhance the system reliability, the single modules are recommended to reduce their failure rates.
- As for the planning modules, it will improve the reliability of the whole system apparently in promotion from once a month to three month, which is the most efficient. As for safety modules, the improvement of the reducing failure in reliability is slight, and the most efficient promotion is to reduce the failure from once a month to three month. However, the improvement of hardware modules and framework module makes the slight impact.
- The safety protection effect should be improved. The experiment shows that when the safety protection module fails, it is difficult to distinguish diverse negative effects. However, the result is unable to reflect the protection effect of the module. The advanced protection module will increase the reliability of the system, which can be discussed in later researches.
- As for the reboot probability related to controlling modules, it is considered not to improve, since the reboot process has slight impact on the improvement of system reliability.
- The backup of planning modules is also recommended to improve the reliability.

VII. CONCLUSION

In this paper, we have introduced an architecture of robot control system. The reliability of the system is related to different modules including planning, safety protection, hardware and framework modules. The system is recommended to improve its reliability in reducing the failure rate of single module and setting up new backup for planning modules. This paper also directs to the improvement of safety protection module in its protection effect, which can be further discussed.

VIII. ACKNOWLEDGE

This work was supported by the XJTLU research development fund projects under Grant RDF140243 and Grant RDF150246, in part by the National Natural Science Foundation of China under Grant No. 61701418, in part by Innovation Projects of The Next Generation Internet Technology under Grant NGII20170301, in part by the Suzhou Science and Technology Development Plan under Grant SYG201516, and in part by the Jiangsu Province National Science Foundation under Grant BK20150376.

REFERENCES

[1] Wang Deyu. Design of Control System for Substation Service Robot[J]. Electronic measurement technology. 2017(5).

[2] Nie Hongyu, Liu Rui, Xue Zhihang. Design of Motion Control System for Magnetic Navigation Inspection Robot[J]. China Test. 2014(S1).

[3] Li Tianyou, Huang Chaoyi, Cai Junyu. The Development and Prospect of Distribution Robot[J]. Distribution & Utilization. 2016(11).

[4] M.W. Spong. Modeling and control of elastic joint robots, Transac- tions of the ASME, J. Dynamic Systems, Measurement and Control, vol. 109, pp. 310-319, Dec. 1987.

[5] Nie Hongyu, Liu Rui. Design of Motion Control System for Magnetic Navigation Inspection Robot[J]. China Test. 2014(S1).

[6] Huangzhen, Kong Linfu, Fang Yue, The theory of parallel robot mechanism discussing control [M], Beijing:mechanical industry press, vol. 29, 1997.

[7] Kwiatkowska, M., G. Norman, and D. Parker. Probabilistic Symbolic Model Checking with PRISM: A Hybrid Approach. in Lecture Notes in Computer Science. 2002.

[8] D. Greer, P. McKerrow, J. Abrantes, Robots in Urban Search and Rescue Operations,ARAA 2002 Australasian Conference on Robotics and Automation, November 2002.

[9] D.S. Kurushin, E.V. Dolgova, R.A. Faizrakhmanov, Simulation bypass obstacles mobile robot,Information-measuring and operating systems, vol. 12, no. 9, pp. 219-221, 2014.

[10] S. V. Dhople, A. Davoudi,P. L. Chapman and A.D.Dominguez- Garcia,Integrating photovoltaic inverter reliability into energy yield estimation with Markov models. Control and Modeling for Power Electronics IEEE Xplore, pp. 1-5, 2010.

[11] Li Jian. Development of 220 kV substation live working robot[J]. Manufacturing Automation. 2013(9).

[12] Zhu Lida, Zhu Chunxia, Cai Guang, PID adjustment in PMAC motion controller [J],Combination of machine tool and automation processing technology, vol. 2, pp. 50-53, 2007.

[13] Deyu. Wang, Design of Control System for Substation Service Robot,Electronic measurement technology, vol. 5, 2017.

[14] Tianyou. Li, Chaoyi. Huang, Junyu. Cai, The Development and Prospect of Distribution Robot,Distribution & Utilization, vol. 11, 2016.

[15] Yangyang.Guo,ResearchonHydraulicServoControlSystemofWater Washing Mobile Robot Based on Fuzzy Control,Shandong Jianzhu University, 2016.