Reliability analysis of mobile robot: a case study

Panagiotis H. Tsarouhas and George K. Fourlas

***Abstract*—** Reliability analysis for mobile robot system is conducted by applying statistical techniques based on failure data. Data collection from the robot and their analysis were valid over a long time of thirty four months. Critical components of the mobile robot with respect to failure frequency and reliability are identified for taking necessary measures for enhancing availability of the system. Reliability at component level and the entire mobile robot were computed. They can potentially be useful tools to improve the current generation of robots and to predict their designs of the next generation.

Keywords*—R*eliability, applied statistics, failure data, mobile robot.

I. Introduction

THE mobile robot is a complex system that consists of numerous components. The reliability of the robot system depends directly of the performance of each component. A successful robot installation has to be safe and reliable; a robot with poor reliability leads to many problems such as high maintenance cost, unsafe conditions and inconvenience [1]. The subject of robot reliability is very complex and there are numerous interlocking variables in evaluating and accomplishing various reliability levels [2]. The reliability analysis of the failure data could be a useful tool to assess the current situation, and to predict reliability for upgrading the operation management of the mobile robot system.

In the literature there are several published articles and books on reliability analysis [3-7]. On the other hand, Dhillon [8] reported that despite the existence of a vast amount of literature on robotic research, not much work has been done on robot system reliability. Carlson and Murphy [9] proposed a new approach and studied the reliability analysis of mobile robots. Khodabandehloo [10] presented the use of systematic techniques such as fault tree analysis (FTA) and event tree analysis (ETA) to examine the safety and reliability of a given robotic system. Dhillon and Fashandi [11] present probabilistic analysis of a system consisting of a robot and its associated safety mechanism. Expressions along with plots for the robot system availability and state probabilities are presented. Moreover, Carreras and Walker [12] used interval method to chalk out the reliability analysis of robot. Hoshino *et al*. [13] proposed an optimal maintenance strategy on the basis of reliability engineering in fault-tolerant multi-robot systems. Bererton and Khosla [14] quantified the gain in productivity of a team of repairable robots compared to a team without repair capabilities based on reliability theory.

The corresponding literature related to the reliability analysis of failure data for mobile robots is quite limited. Nourbakhsh [15] describes a set of four autonomous robots used for a period of five years as full-time museum docents. Their robots reached a mean time between failures (MTBF) of 72 to 216 hours. Carlson *et al.* [16] proposed a new approach, where the reliability analysis of mobile robots was studied and suggestions based on mean time between failures (MTBF), mean time to repair and downtime, for system performance, were given. In another study, Tomatis [17] maximized the autonomy and interactivity of the mobile platform (with10 autonomous robots) while ensuring high robustness, reliability and performance. The result pointed out that their MTBF was around 7 hours. Stancliff *et al.* [18] estimated mission reliability for a repairable robotic system and then extended the approach to multi-robot system design and presented the first quantitative support for the argument that larger teams of less-reliable robots can perform certain missions more reliably than smaller teams of more-reliable robots. In other study, Starr et al. [19] surveyed failure and maintenance reports from two large automotive plants. The reports covered 200 robots representing five manufacturers over a period of 21 weeks. The robots were found to be down for repair or maintenance for 3.95 hrs per week per manufacturing line in the first plant and 1.74 hrs in the second.

In this study, reliability analysis is conducted for mobile robot system by applying statistical techniques on field failure data. Data collection from the robot and their analysis were valid over a long time of thirty four months. Critical components of the mobile robot with respect to failure frequency and reliability are identified for taking necessary measures for enhancing availability of the system. Reliability at component level and the entire mobile robot were computed. They can potentially be useful tools to improve the

This research is implemented through the Operational Program "Education and Lifelong Learning" and is co-financed by the European Union (European Social Fund) and Greek national funds. The work is part of the research project entitled «DIAGNOR - Fault Diagnosis and Accommodation for Wheeled Mobile Robot» of the Act "Archimedes III - Strengthening Research Groups in TEI of Central Greece".

P. H. Tsarouhas, is with the Department of Supply Chain Management & Logistics, Technological Educational Institute of Central Macedonia, Katerini 601 00, Greece, (phone: +30- 23510-47862; fax: +30-23510-47860; e-mail: ptsarouhas@teicm.gr).

G. K. Fourlas is with the Department of Informatics, Technological Educational Institute (T. E. I.) of Central Greece, Lamia 35100, Greece, (phone: +30-22310-60186; fax: +30-22310-33945; e-mail: gfourlas@teilam.gr)

ISBN: 978-1-61804-226-2

current generation of robots and to predict their designs of the next generation.

II. Description of the Mobile Robot System

A wheeled mobile robot is usually an embedded control platform, which consists of an on-board computer, power, motor control system, communications, sonars, cameras, laser radar system and sensors such as gyroscope, encoders, accelerometer etc., Fig. 1.

In this study, the mobile robot Pioneer 3-AT was used as a robotic platform. This robot is a four wheel skid – steering vehicle actuated by two motors, one for the left sided wheels and the other for the right sided wheels. The wheels on the same side are mechanically coupled and thus have the same velocity. Also, they are equipped with two high resolution optical quadrature shaft encoders mounted on reversible-DC motors which provide rotational speeds of the left and right wheels ω_L and ω_R respectively. Moreover the mobile robot is equipped with an Inertial Measurement Unit (IMU) which provides the forward linear acceleration and the angular velocity as well as the angle θ between the mobile robot axle and the x axis of the mobile robot.

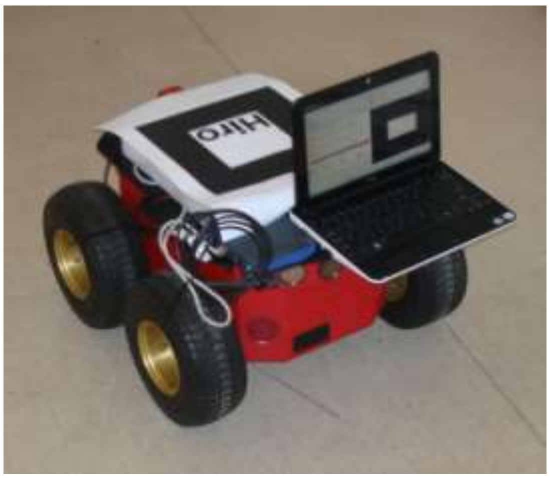


Fig. 1 The mobile robot Pioneer 3-AT

As a fault, it can be considered any unpermitted deviation from the normal behavior of the system. It is consider five different types of faults: (a) fault in the encoder reading F1, (b) gradual loss of tire pressure F2, (c) loss of wireless communication between the robot on-board computer and the base station F3, (d) gradual discharge of the battery F4, and (e) malfunction of the motor F5.

III. Field Failure Data

Failure and repair data of the robotic system were collected from the files of the researchers by the end of each experimental day. The mobile robot operates continuously ten-hour during each day, five days per week. According to the records, a total of 117 failures were determined for the entire system. Thus, the failure and repair data cover a period of 34 mounts. The records include the failures occurring per day, the action taken to repair the failure, the down time, and the exact time of failure. Therefore, there is the exact time both for the component failure and the repair of this failure. This means that the precision in computing the time-between-failures (TBFs) and the time-to-repair (TTRs) of failures. The TBFs are recorded in hours, whereas the TTRs in minutes.

In Fig. 2, the faults of the mobile robot with respect to failures frequency were shown. The following observations were made: (a) the encoder (F1) has the highest number of failures 45%, (b) the second important is the tires (F2) that has 30% of failures, and (c) the encoder (F1) and the tires (F2) in diagram stand for the 75% of all the failures of system. It is noteworthy that since the motor (F5) present only two failures there is no need for further analysis.

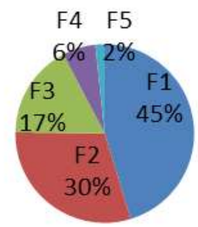


Fig. 2 The components with respect to failures frequency

In the reliability theory the main features are the mean time between failure (MTBF) and the mean time to repair (MTTR), and are given respectively by

$$MTBF = \frac{1}{N}\sum_{i=1}^{N} TBF_i \tag{1}$$

$$MTTR = \frac{1}{N}\sum_{i=1}^{N} TTR_i \tag{2}$$

where N is the total number of failures/repairs studied within the frame of this investigation.

The availability of the mobile robot machine is defined as

$$Availability = \frac{MTBF}{MTBF + MTTR} \tag{3}$$

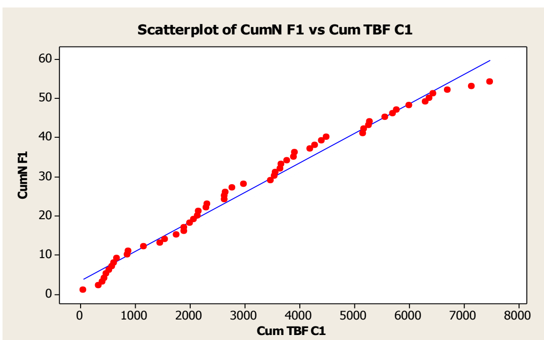
Table1 presents the number of failures, the MTBF/MTTR, and the availabilities of the faults for the mobile robot. The following observations were made: (a) the lowest availabilities are observed on the tire (F2) with 99.95% and on the wireless communication (F3) with 99.96%. (b) The MTBFs range from 138.7 hours to 936 hours, whereas the MTTRs are between 2.26 to 8.15 minutes.

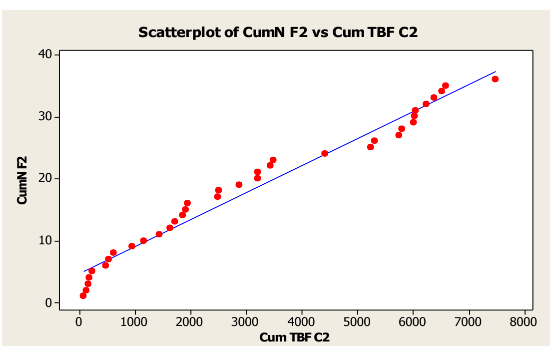
Table 1 Availabilities for the mobile robot at fault level

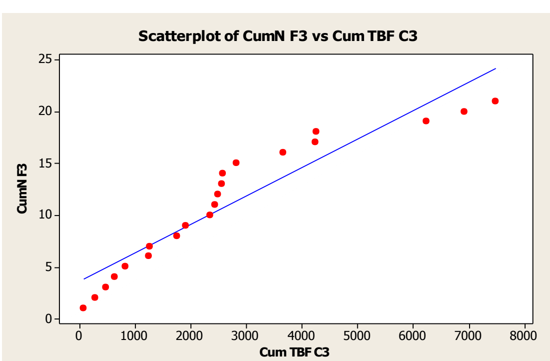
Faults	Failures	MTBF	MTTR	Availability
F1	53	138.7	2.264	0.999732977
F2	35	208	5.143	0.999599466
F3	20	356.6	8.15	0.999637329
F4	7	936	7.286	0.999886513

IV. Data Analysis

After collection, sorting and classification of the data, the validation of the assumption for independent and identically distributed (*iid*) nature of the TBF are verified using trend test and serial correlation test. The trend test for TBFs is done graphically by plotting the cumulative frequency of failure against the cumulative TBF respectively. In case of trend test of TBF, concave upward curve indicates that the system is deteriorating and concave downward curve indicates the system is improving. If the curve is approximately a straight line, then the data is identically distributed and free from trends.







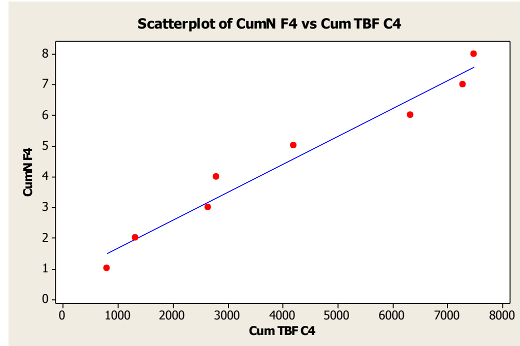
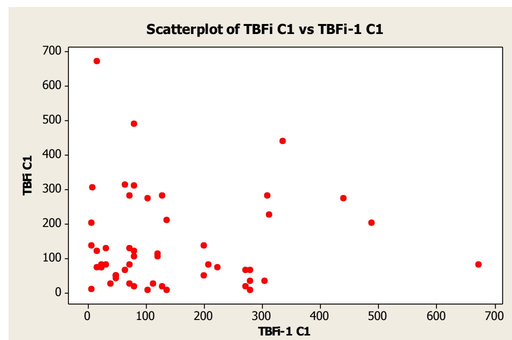
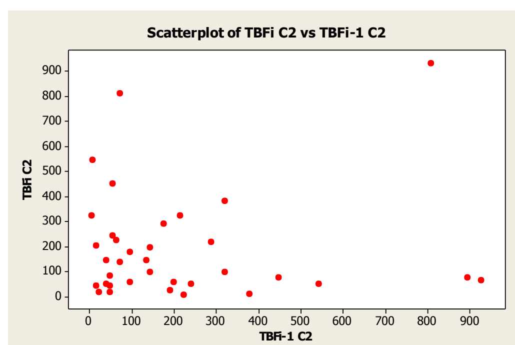
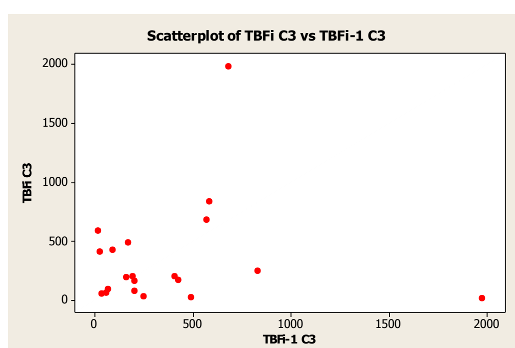


Fig. 3 Trend Test plot for TBF of mobile robot

The serial correlation test can be performed graphically by plotting the i^{th} TBF against $(i\text{-}1)^{th}$ TBF for i = 1, 2... n, where n is the total number of failures. If the points are scattered without any clear pattern, then the data are independent i.e. free from serial correlation. In case where the failure data is dependent or correlated, the points should lie along a line.







ISBN: 978-1-61804-226-2

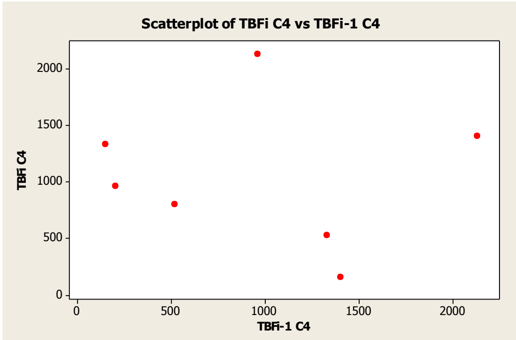


Fig. 4 Serial Correlation Test for TBF of mobile robot

In Fig. 3 and 4, the trend tests and serial correlation tests plot for TBF data sets of the faults are shown, respectively. Thus, from these tests it is obvious that the TBFs of the mobile robot are free from the presence of trends and serial correlations.

V. Reliability Analysis

Reliability is the probability that a system will perform a required function, under stated conditions, for a stated period of time t. Thus, reliability is the probability of non-failure in a given period of time. Then, the reliability can be expressed as [20],

$$R(t) = P(T \geq t) \tag{4}$$

The mobile robot consists of five components in series, and in a serial configuration, all the consisting components of the system should be operating to maintain the required operation of the robot. A failure of a single component of the robot will cause failure of the whole system. Thus, the reliability of the entire mobile robot can be calculated with the following equation:

$$R_{Robot}(t) = R_1(t) * R_2(t) * ... * R_5(t) = \prod_{i=1}^{5} R_i(t) \tag{5}$$

To identify the distributions of the trend-free failure data between several theoretical distributions (i.e. Weibull, lognormal, exponential, loglogistic, normal and logistic distribution), the maximum likelihood estimation method was used per candidate distribution and assessed its parameters by applying a goodness-of-fit test Anderson-Darling. The results of best-fit distributions and their estimated parameters for TBF are shown in Table 2.

Table 2 Best–fit distribution for TBF data sets and estimated parameters

Faults	Best fit distribution	Parameters	
F1	Exponential	β=0.007	
F2	Lognormal	β=4.6924	θ=1.2866
F3	Lognormal	β=5.2634	θ=1.2721
F4	Weibull	β=1.7603	θ=1171.72

In Fig. 5 the reliability diagram for TBF of the robotic system are displayed. The following observations are made: (a) the reliability of the mobile robot, in 5 hours of operation is 94.60%, and in 40 hours of operation is 52.44%. (b) The highest reliability is on the battery (F4), whereas the lowest is observed on the encoder (F1).

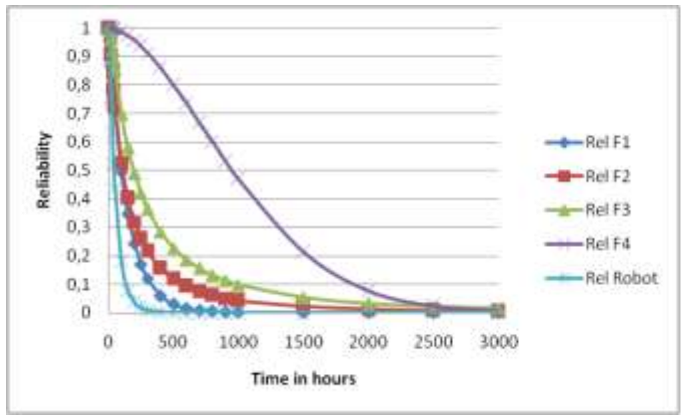


Fig. 5 Reliability diagram for TBF of the mobile robot

VI. Conclusion

The main research findings can be summarized as follows: (a) whereas the availabilities of the components for the mobile robot are high, the reliabilities are low as well as the entire system. (b) The MTBFs range from 138.7 hours (F1) to 936 hours (F4). (c) The failure data are free from the presence of trends and serial correlations, meaning the TBFs are independent and identically distributed. (d) The highest reliability is on the battery (F4), whereas the lowest is observed on the encoder (F1). (e) The reliabilities of the components and their parameters are calculated.

Therefore, to avoid the inconvenient impact of the faults on the mobile robot, it is strongly recommended to increase the reliabilities of the encoder (F1) and then of the tires (F2), as well as the entire system.

References

[1] N. Kumar, J.-H. Borm, A. Kumar, "Reliability analysis of waste clean-up manipulator using genetic algorithms and fuzzy methodology", Computers & Operations Research, Vol. 39, 2012, pp. 319-319.

[2] S.P. Sharma, N. Sukavanam, N. Kumar, A. Kumar, "Reliability analysis of complex robotic system using Petri Nets and Fuzzy Lambda-Tau

Methodology", Engineering Computations, 2010;Vol. 27, No 3, 2010, pp. 54–364.
[3] B. Foucher, D. Das, J. Boulie, B. Meslet, "A review of reliability prediction methods for electronic devices. Microelectronics Reliability", Vol. 42, No 8, 2002, pp. 1155-1162.
[4] S.E. Rigdon, A.P. Basu, Statistical methods for the reliability of repairable systems. John Wiley and Sons, Inc, 2000, pp. 73-110.
[5] M. Rausand, and A. Høyland, System Reliability Theory, Models, Statistical Methods, and Applications. Wiley Series in Probability and Statistics, 2004, pp. 35-74.
[6] P. Tsarouhas, I. Arvanitoyannis, Z. Ampatzis, "A case study of investigating Reliability and Maintainability in a Greek Juice bottling Medium Size Enterprise (MSE)", Journal of Food Engineering. Vol. 95, 2009, pp. 479-488.
[7] MIL-HDBK-338B, Electronic Reliability Design Handbook. Department of Defense, USA, (1998), pp. 44-97.
[8] B.S. Dhillon, O.C. Anude, "Robot safety and reliability: a review. Microelectronics Reliability", Vol. 3, No 3, 1993,pp. 413–29.
[9] J. Carlson, and R.R. Murphy, "Reliability analysis of mobile robots", In Proceedings of the IEEE annual reliability and maintainability symposium, Vol. 1, 2003, pp. 274–281.
[10] K. Khodabandehloo, "Analysis of robot systems using fault and event trees: case studies", Reliability Engineering and System Safety, Vol. 53, No3, 1996, pp.247–64.
[11] B.S. Dhillon, A.R.M. Fashandi, "Robotic system's probabilistic analysis", Microelectronics Reliability, Vol. 37, No2, 1997, pp. 211–224.
[12] C. Carreras, I.D. Walker, "On interval methods applied to robot reliability quantification", Reliability Engineering and System Safety, Vol. 70, No3, 2000, pp. 291–303.
[13] S. Hoshino, H. Seki, and J. Ota, "Optimal Maintenance Strategy in Fault-Tolerant Multi-Robot Systems", IEEE/RSJ International Conference on Intelligent Robots and Systems September 25-30, 2011, pp. 2314-2320.
[14] C. Bererton, and P. Khosla, "An analysis of cooperative repair capabilities in a team of robots", Proc. 2002 IEEE Int. Conf Robotics and Automation, 2002, pp. 476-486.
[15] I. Nourbakhsh, "The mobot museum robot installations", In Proceedings of the IEEE/RSJ IROS 2002 Workshop on Robots in Exhibitions, 2002, pp. 14-19.
[16] J. Carlson, R.R. Murphy, and A. Nelson, "Follow-up analysis of mobile robot failures", Proceedings of the IEEE International Conference on Robotics and Automation (ICRA' 04), Vol. 5, 2004, pp. 4987-4994.
[17] N. Tomatis, G. Terrien, R. Piguet, D. Burnier, S. Bouabdallah, and R. Siegwart, "Design and system integration for the expo.02 robot", In Proceedings of the IEEE/RSJ IROS 2002 Workshop on Robots in Exhibitions, 2002, pp. 67-72.
[18] S.B. Stancliff, J.M. Dolan, and A. Trebi-Ollenu, "Mission reliability estimation for repairable robot teams", International Journal of Advanced Robotic Systems, Vol. 3 No2, 2006, pp. 155-164.
[19] A. Starr, R. Wynne, and I. Kennedy, "Failure analysis of mature robots in automated production", Proceedings of the Institution of Mechanical Engineers-Part B (J. Eng. Manuf.), Vol. 213, 1999, pp. 813–824.
[20] P. Tsarouhas, "Reliability, Availability, and Maintainability (RAM) analysis in food production lines: a review", International Journal of Food Science & Technology, Vol. 47, No11, 2012, pp. 2243-2251.

Dr Panagiotis Tsarouhas, Dipl. Eng., PhD is **Assistant Professor** at Technological Educational Institute of Central Macedonia (Greece), Department of Supply Chain Management & Logistics and a tutor in postgraduate course on Quality Assurance in Hellenic Open University. He received his Diploma in Mechanical Engineering from Universita degli studi di Napoli Federico II (Italy), and both Ph.D. and M.Sc. from the Department of Mechanical and Industrial Engineering from the University of Thessaly in Volos, Greece. For about 10 years he was at the Technical Department as production and maintenance operation head in food industry 'Chipita International SA' in Lamia, Greece. He has about 23 years research/teaching experience, and more than 40 research papers in international journals, book chapters and conference proceedings. He has been involved in many research and practical projects in the field of reliability analysis and maintenance engineering. His areas of interest are reliability & maintenance engineering, quality engineering, and supply chain management.

George K. Fourlas is an **Assistant Professor** at the Department of Informatics of Technological Educational Institute (T.E.I.) of Central Greece, Lamia, Greece. He received his BSc in Physics from the University of Patras, Greece in 1991, MS in Control of Industrial Processes from the University Paris XII – Val de Marne, France in 1993 and PhD in Fault Diagnosis of Hybrid Systems from School of Mechanical Engineering at National Technical University of Athens (NTUA), Greece in 2003. His research interest is mainly focused on: fault diagnosis and fault tolerance of hybrid systems, failure diagnosis, robotics, air traffic management systems, hybrid control systems, embedded systems and microcontrollers, power systems.