Mapping the impact of faults in a multi-robot team

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***Abstract*—Hardware failure can have significant impact on the performance of a multi-robot team. The work presented here provides a preliminary assessment of this impact based on experiments conducted with physical robots. Two types of hardware failure are considered: motor failure and laser sensor failure. These can be *permanent* (where the robot does not recover during the mission) or *temporary* (where the robot does recover). Results show that permanent motor failure and laser sensor faults decrease the success rate of task completion to varying extents and laser sensor faults also cause significant errors in measuring distances travelled by the robot experiencing these faults. While these results are not unexpected, the contribution of this work is in laying out a structured baseline that will be used in the near future for comparison of various recovery strategies.**

***Index Terms*—multi-robot teams; fault tolerance**

I. Introduction

A multi-robot team is expected to coordinate behaviours amongst team members in order to complete a set of tasks in such a way that the team outperforms what a single-robot system can achieve. Distribution of tasks amongst multi-robot team members is a well-studied problem. Much work has focused on producing algorithms to optimise *task allocation*, within restricted settings—without evaluating the effectiveness of the allocation when tasks are actually executed and without considering the impact if individual robots experience hardware failure during a mission. Our prior work has pushed beyond the *allocation* stage and concentrated on a systematic and empirical study of the impact of market-based task allocation mechanisms when applied to a diverse landscape of missions and environments [1]–[5]. The emphasis in that work on experimental results, particularly results obtained from physical robot teams, has led to questions of *fault tolerance* in a multi-robot team and motivated our present line of research.

The study presented here investigates the impact on team performance when one of the robots on the team experiences hardware failure, such as loss of ability to move ("motor failure") or loss of sensing ("sensor failure"). We emulate failure in a controlled way, so that we can measure the impact of (planned) hardware faults on team performance metrics. Results of experiments conducted with physical robots reveal the changes in outcome when faults are "permanent" (robot does not recover during a mission) as compared to "temporary" (robot recovers during the mission).

II. Background

Fault tolerance refers to the ability of a system to continue to operate, albeit perhaps at a lower performance level, when the system suffers from undesired situations (e.g. internal faults and/or interference from the outside environment) [6]. A brief survey of experiments conducted with multi-robot teams examining the effects of faulty team members reveals that a reliable and fault-tolerant multi-robot system comes at a cost. There are three main questions which need to be addressed [7]: (1) how to detect whether robots have faults or not; (2) how to identify or diagnose robot failures; and (3) how to recover from the failures.

Winfield & Nembrini [8] explore fault tolerance in a robot swarm by using their *Failure Mode and Effect Analysis (*FMEA*)* approach [9]. They test a containment task and analyse the effects hazards have on a robot swarm. They show that partial failure is more harmful than complete failure, e.g. a robot with broken motors will have an anchoring effect, whereas complete failure, which causes the robot to become a static obstacle, has less serious effects on the whole system.

Bjerknes & Winfield [10] study a swarm taxis task in which a team of robots form a coherent group and then move toward a beacon. They consider three failure modes: complete failure of individual robots; failure of a robot's infrared (IR) sensors; and failure of a robot's motors only. Results show that IR sensor failure slows down the progress of the swarm, but the whole swarm still reaches the beacon; whereas motor failures cause the swarm to hover around the failed robots, eventually escaping the influence of the failure robots.

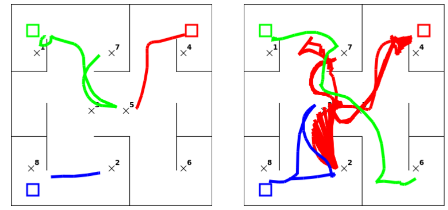
Timmis et al. [11] propose a self-healing approach. Using the case study of [10], they consider motor failure due to lack of power, where the remaining power is enough to support communication. Faulty robots emit a faulty signal to their neighbours and then healthy robots share their energy by recharging the drained batteries of faulty robots. As evaluated in simulation, the self-healing system works well even when half the robots in the swarm experience low-energy faults.

Kamel et al. [12] present fault-tolerant cooperative control strategies to deal with actuator faults in a multi-robot formation task, and later work [13] considers partial actuator faults. When complete failure occurs, the formation outcome changes; whereas partial failure results in slower performance but eventual achievement of the desired formation.

Our long term research goal focuses on generating robust strategies for recovering from partial and total motor and sensor failures. Here we present empirical baseline results obtained from a number of experiments conducted on physical robots where faults were emulated.

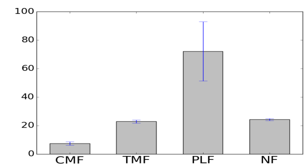
(a) arena (b) robot

Fig. 1. Experimental setup

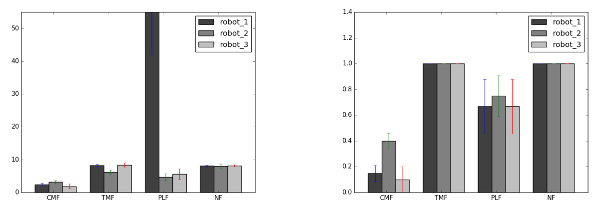


(a) CMF (b) PLF

Fig. 2. Trajectories travelled by sample robots impacted by (a) complete motor failure (CMF) and (b) partial laser failure (PLF) in one mission configuration (scenario 1, distributed start, MR-CT-SA configuration): each mission involves 3 robots performing 8 exploration tasks ($x_1..x_8$).



(a) total distance travelled



(b) distance per robot (c) success rate per robot

Fig. 3. Statistics from one mission configuration (MR-CT-SA, distributed start, scenario 1)

III. Approach

In order to investigate the impact of hardware failure in a multi-robot team, we induce different types of failures in the ”faulty” robot at a randomly generated time point. We define two sets of parameters to classify each failure mode: *Permanent Failure* (which cannot be recovered by the robot itself and will persist for the remainder of the experiment) versus *Temporary Failure* (which only exists for a short period of time and the robot will recover autonomously without any help); and *Complete Failure* (where the device is entirely broken) versus *Partial Failure* (where the device works but with performance degradation). This work investigates two types of hardware failure (motor and laser sensor) in three failure modes: complete (permanent) motor failure (*CMF*); temporary motor failure (*TMF*); or permanent laser sensor failure (*PLF*). No failure (*NF*) is included for comparison.

To evaluate the impact of each failure type, we consider metrics that measure the performance of both individual robots and the team as a whole. Here we focus on the **distance travelled** by the robots executing allocated tasks; and **success rate** of task completion by each robot.

IV. Experiments and Results

We conducted 320 trails using the MRTeAm framework [4], [14] and Turtlebot 3 Burger platform performing exploration tasks in an office-like environment (Figure 1). Our ”faulty” robot employs a modified controller which will induce failure after a randomly generated time, chosen from a Gaussian distribution, and last for a random amount of time[1]. Experimental missions have 8 tasks allocated to 3 robots using the *Sequential Single Item (SSI)* auction mechanism [15]. Missions are classified according to scenario and starting condition. Scenarios are defined by several parameters: *single-robot (SR)* versus *multi-robot (MR)* tasks; *independent (IT)* versus *constrained (CT)* tasks; and *static (SA)* versus *dynamic (DA)* task arrival (before or during mission execution, respectively).

A sample set of results is shown in Figures 2 and 3. Figure 2 illustrates trajectories travelled by sample robots impacted by complete motor failure (CMF) (Fig. 2a) and partial laser sensor failure (PLF) (Fig. 2a) in one mission configuration (scenario 1, distributed start, MR-CT-SA configuration). Figure 3 illustrates performance metrics for the same mission. Figure 3a shows the total distance travelled by the team as a whole, indicating clearly that when there is a partial laser sensor failure, the faulty robot has trouble localising and travels much further than it needs to, contributing to an outsize distance for that experimental condition. This is highlighted by the red path shown in Figure 2b and by the tallest (dark) bar in Figure 3b. Figure 3c shows the success rate, which is measured as the percentage of assigned tasks that were completed. When failure is temporary and there are no failures, then all assigned tasks are completed. Complete motor failure has a more detrimental effect than partial laser failure.

[1] The parameters used: time of inducing failure: $\mu = 20, \sigma = 5$, and duration of temporary failure: $\mu = 10, \sigma = 2$. Future work will compare other distributions, such as Poisson.

V. Summary

We have shown preliminary results of baseline experiments designed to illustrate the impact of various types of hardware failures on the performance metrics achieved by a multi-robot team. A range of scenarios and mission configurations have been produced, though space constraints here allow showing only a sample for one such configuration. A more comprehensive report with complete results is under preparation. Our next steps involve development of response strategies when failures occur, followed by experimental evaluation of our strategies in comparison with others mentioned in Section II.

REFERENCES

[1] E. Schneider, O. Balas, A. T. Özgelen, E. I. Sklar, and S. Parsons, "An Empirical Evaluation of Auction-based Task Allocation in Multi-Robot Teams (Extended Abstract)," in *Proceedings of the 13th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, Paris, France, May 2014.

[2] ——, "Evaluating auction-based task allocation in multi-robot teams," in *Workshop on Autonomous Robots and Multirobot Systems (ARMS) at Autonomous Agents and MultiAgent Systems (AAMAS)*, Paris, France, May 2014.

[3] E. Schneider, E. I. Sklar, and S. Parsons, "Evaluating multi-robot teamwork in parameterised environments," in *Towards Autonomous Robotic Systems: 17th Annual Conference (TAROS)*. Springer, 2016.

[4] E. Schneider, E. I. Sklar, S. Parsons, and A. T. Özgelen, "Auction-based task allocation for multi-robot teams in dynamic environments," in *Towards Autonomous Robotic Systems: 16th Annual Conference (TAROS)*. Springer, 2015.

[5] D. Zhang, E. Schneider, and E. I. Sklar, "A cross-landscape evaluation of multi-robot team performance in static task-allocation domains," in *Towards Autonomous Robotic Systems: 20th Annual Conference (TAROS)*. Springer, 2019, pp. 261–272.

[6] L. E. Parker, "Reliability and fault tolerance in collective robot systems," *Handbook on Collective Robotics: Fundamentals and Challenges, Pan Stanford Publishing, Singapore*, 2012.

[7] D. Crestani, K. Godary-Dejean, and L. Lapierre, "Enhancing fault tolerance of autonomous mobile robots," *Robotics and Autonomous Systems*, vol. 68, pp. 140 – 155, 2015.

[8] A. F. T. Winfield and J. Nembrini, "Safety in numbers: Fault tolerance in robot swarms," *International Journal on Modelling Identification and Control*, vol. 1, no. 1, pp. 30–37, 2006.

[9] W. Kenneth, "The fmea pocket handbook," 2004.

[10] J. D. Bjerknes and A. F. T. Winfield, *On Fault Tolerance and Scalability of Swarm Robotic Systems*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 431–444.

[11] J. Timmis, A. Ismail, J. Bjerknes, and A. Winfield, "An immune-inspired swarm aggregation algorithm for self-healing swarm robotic systems," *Biosystems*, vol. 146, pp. 60 – 76, 2016, information Processing in Cells and Tissues.

[12] M. A. Kamel, Y. Zhang, and X. Yu, "Fault-tolerant cooperative control of multiple wheeled mobile robots under actuator faults," *IFAC-PapersOnLine*, vol. 48, no. 21, pp. 1152 – 1157, 2015, 9th IFAC Symposium on Fault Detection, Supervision andSafety for Technical Processes SAFEPROCESS 2015.

[13] M. A. Kamel, X. Yu, and Y. Zhang, "Fault-tolerant cooperative control design of multiple wheeled mobile robots," *IEEE Transactions on Control Systems Technology*, vol. 26, no. 2, pp. 756–764, March 2018.

[14] E. Schneider, "Mechanism selection for multi-robot task allocation," Ph.D. dissertation, University of Liverpool, 2018.

[15] S. Koenig, C. Tovey, M. Lagoudakis, V. Markakis, D. Kempe, P. Keskinocak, A. Kleywegt, A. Meyerson, and S. Jain, "The power of sequential single-item auctions for agent coordination," in *21st Natl Conf on Artificial Intelligence (AAAI)*, vol. 2, 2006.