Integrated Trajectory Planning and Fault Detection for a Skid-Steered Mobile Robot deployed in Post-Disaster Scenarios

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Technologies for Defense and Security

TechDefense 2024 - Napoli, Italy

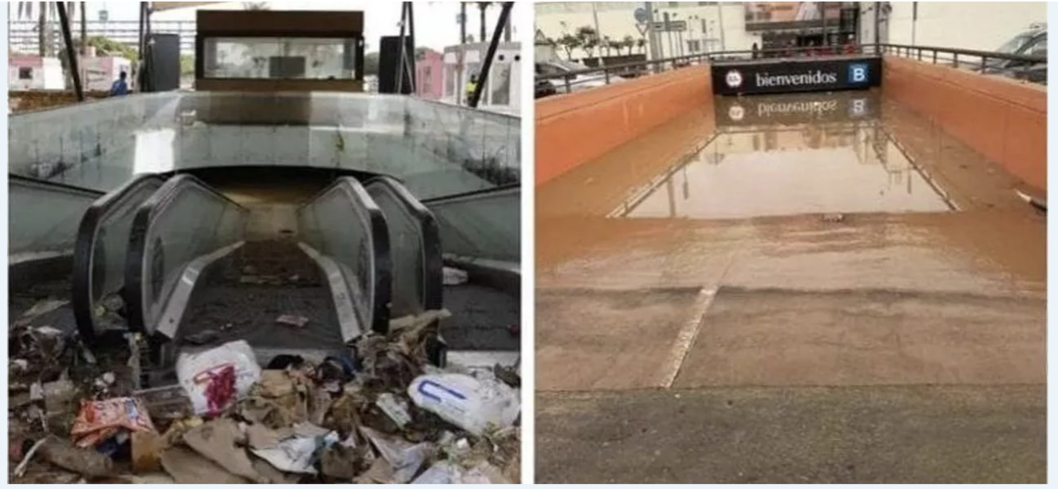
Natural Disasters: A Threat to Public Safety







The most recent



Robotic platforms for rescue and first aid operations

What can we do?

- Implement an effective **emergency response system.**
- Autonomous robotic platforms for first aid and rescue missions after disasters.

Advantages of using robotic systems

- Robots can reach places that are inaccessible to human operators.
- The use of robots instead of human operators can significantly increase the safety of rescue personnel and the effectiveness of rescue operations.

State of Art

Use of robots in rescue operations

Some examples are:

- the attacks of September 11 2001 (New York, USA);
- the landslide in La Conchita (U.S.) 2005;
- the Hurricanes Katrina (USA) and Wilma (USA) both in 2005;
- the Midas Gold Mine collapse (U.S.) 2007;
- Fukushima power plant nuclear disaster in 2011 (JPN);

Current status

Nowadays, the average time between the occurrence of a disaster and the actual deployment of a robot is around 6.5 days, much longer than the 48 hours that represent the peak of the mortality curve.

Technical issues (among others)

- The reasons for this delay depend on many factors:

A) limited autonomy in terms of robot intelligence, power and mobility;

B) insufficient integration with the rescue coordination center

C) limited capability to coordinate many robotic units deployed in the same operational scenario

Research Projects

- *Resilient and Secure Networked Multivehicle Systems in Adversary Environments granted by the Italian Ministry of University and Research (MUR) within the PRIN 2022 program and European Union - Next Generation EU*
- *Cooperative Heterogeneous Multi-drone SYStem for disaster prevention and first response* granted by the Italian Ministry of University and Research (MUR) within the PRIN 2022 PNRR program, funded by the European Union through the PNRR program

Objectives

- We address some of the various technical and technological issues that currently limit the use of robotic systems in disaster relief in order to provide a proof of concept for the entire (multi)-robotic system.

Proposal keypoints

Problem specifically addressed

This paper proposes a fault detection and isolation system to improve the reliability and safety of unmanned ground vehicles during emergency operations.

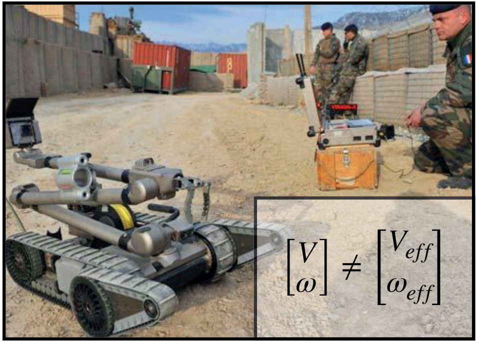
Application aspect

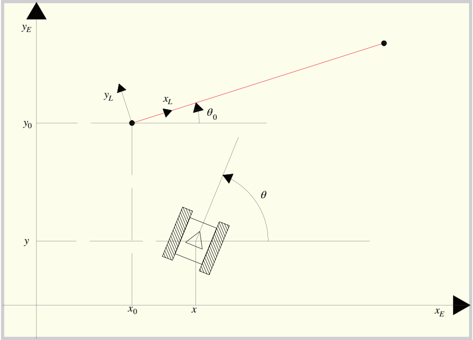
The algorithm can distinguish between actuator and sensor faults and in the case of a sensor fault a reconfiguration strategy is suggested.

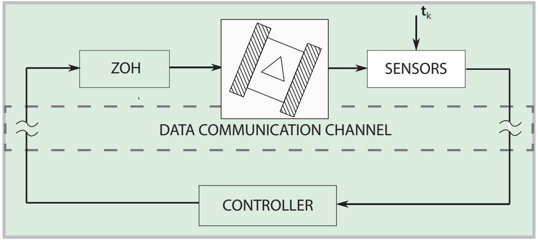
Theoretical aspect

Using some set-based mathematical properties of feasible trajectories, a multivariate logic with low computational complexity is used for FDI purposes.

Closed-loop dynamics : ingredients







Linear Time Invariant Trajectory Tracking Controller

Closed-loop dynamics : result

Discrete uncertain system

The closed-loop dynamics of the trajectory tracking error can be rewritten in a conservative approximation as an uncertain system with norm-bound uncertainty

$$\xi_{k+1} = \phi \xi_k + H_d d_k + B_p p_k, \tag{1}$$

$$p_k = \Delta_k q_k, \tag{2}$$

$$q_k = \Sigma_q \xi_k, \tag{3}$$

where $\|\Delta_k\| < 1 \ \forall k \geq 0$, where ϕ, H_D, B_p, Σ_q are matrix of proper dimensions.

Constraints

$$\xi \in \Omega_\xi, \ \Omega_\xi = \{\xi \in \mathcal{R}^{n_\xi} : \xi^T S_\xi \xi \leq 1, \ S_\xi > 0\}, \tag{4}$$

$$d \in \Omega_d, \ \Omega_d = \{d \in \mathcal{R}^{n_d} : d^T M_d d \leq 1, \ M_d > 0\}, \tag{5}$$

D-invariant region

Ellipsoidal Set

- The system (1)-(3) is asymptotically stable.
- Let us assume that according to [1] the following positively robust *D*-invariant ellipsoidal region can be defined

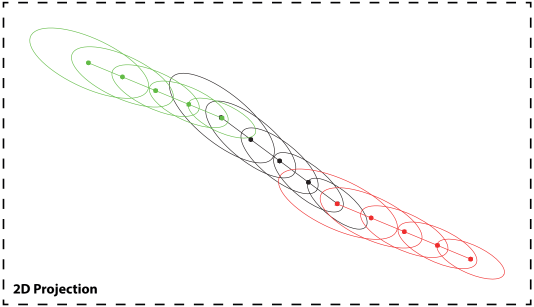
$$\Gamma_0 = \{\delta\xi \in \mathcal{R}^{n_\xi} : \delta\xi^T P_0 \delta\xi \leq 1 \ \ P_0 \geq 0\} \subseteq \Omega_\xi. \quad (6)$$

Invariant Property

- If $\xi(0) \in \Gamma_0$ the state ξ belongs to Γ_0 for all $t \geq 0$, regardless of the uncertainties and admissible disturbances.

[0][1] Kolmanovsky, Ilya, and Elmer G. Gilbert. "Theory and computation of disturbance invariant sets for discrete-time linear systems." Mathematical problems in engineering 4 (1998): 317-367.

Feasible Trajectory



- If the state $\xi(0)$ along a feasible trajectory belongs to a subset of Γ_0, then $\xi(t)$ for all $t \geq 0$ remains independent of the uncertainties and permissible disturbances in Γ_0.
- In this paper we used the feasible trajectory planning approach proposed in [2]

[0] [2] Scordamaglia, Valerio, Vito Antonio Nardi, and Alessia Ferraro. "A feasible trajectory planning algorithm for a network controlled robot subject to skid and slip phenomena." 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). IEEE, 2019.

FDI Algorithm: Proposal

Multivariate threshold logic

It is possible to associate the occurrence of a fault with the violation of (6) condition. Thus, in each time instant t_k the following logic is considered:

$$\|\xi_k\|_{P_0}^2 = \xi_k^T P_0 \xi_k \leq 1 \ (\textit{healthy condition}) \tag{7}$$

$$\|\xi_k\|_{P_0}^2 = \xi_k^T P_0 \xi_k > 1 \ (\textit{faulty condition}) \tag{8}$$

The proposal is to use the quadratic function used to define the Kolmanovsky region as multivariate logic to detect and isolate robot malfunctions.

Fault Detection Isolation and Reconfiguration Strategy

- Proposed approach requires a duplex sensors architecture
- Assume that the hypothesis of no simultaneous faults is valid.

Sensor fault case

- Fault of any sensor.
- Fault detection occurs when the measurements differ in a non-negligible manner.
- Fault isolation is based on the quadratic function value (7)-(8).
- The feedback measurements come only from the labeled healthy sensor.

Actuator fault

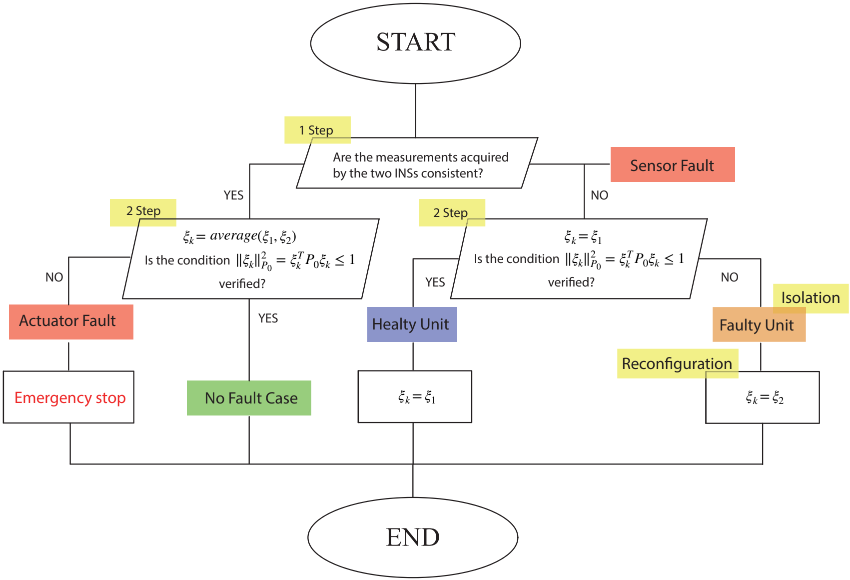
- Fault of any part of the robot that changes the motion capabilities
- Fault detection is performed using the quadratic function (7)-(8).
- Fault is declared as unrecoverable and the robot is stopped.

Numerical Results

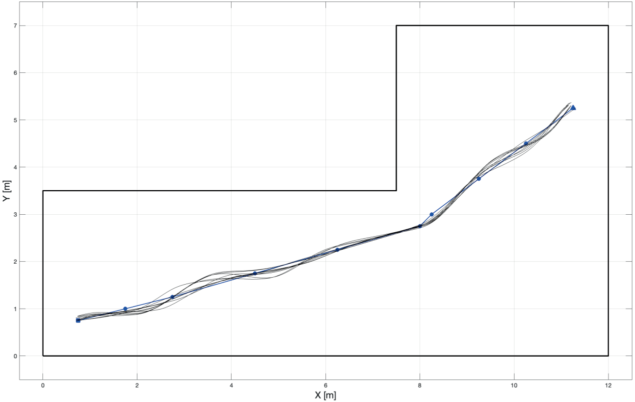
Assumptions

- we have considered the mathematical model of a skid-steered tracked mobile robot subject to sliding effects.
- the geometric parameters are taken from the real Jaguar V4 by Dr.Robot; the effective velocities of the robot differ from the control velocities of $\pm 25\%$
- the robot is equipped with two INS units which are used to estimate the robot's position and orientation
- the trajectory tracking control is implemented on a remote ground station connected to the robot via an 802.11n wireless communication network using the TCP/IP protocol stack
- a delay of up to 300% of the sampling time is taken into account
- a proportional-integral (PI) control law was considered for trajectory control and the robust ellipsoidal D-invariant region (6) was computed

Algorithm flowchart



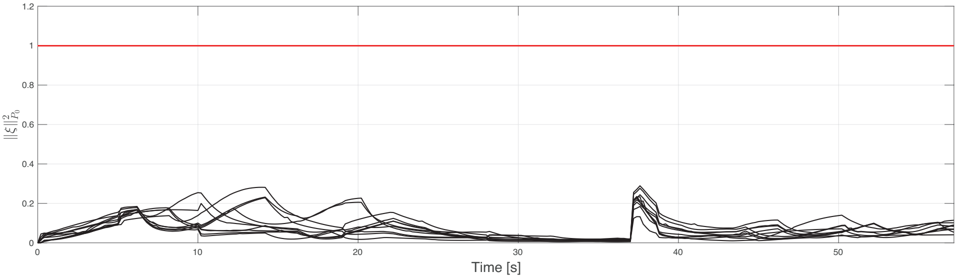
No fault case : False Alarm Rate Analisys



10 simulations were performed in which the initial position and orientation of the robot were varied with respect to the given trajectory.

The black solid lines represent the trajectories performed by the robot during the simulations.

No fault case : False Alarm Rate Analisys

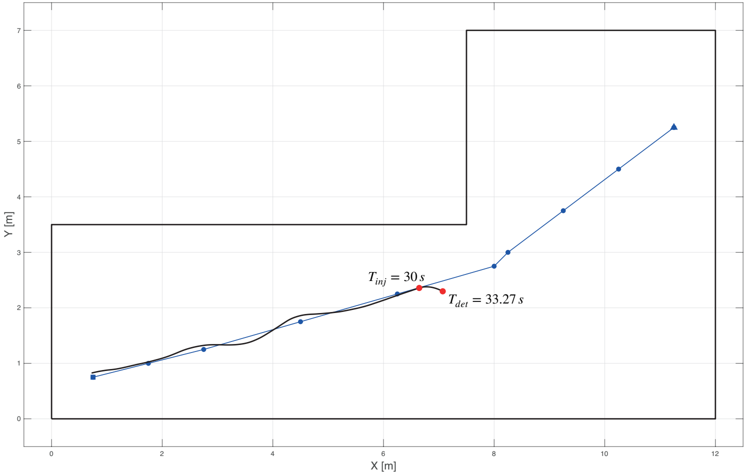


Red line represents the bound condition. Black solid lines represent the values of $\|\xi\|^2_{P_0}$ used for Fault detection.

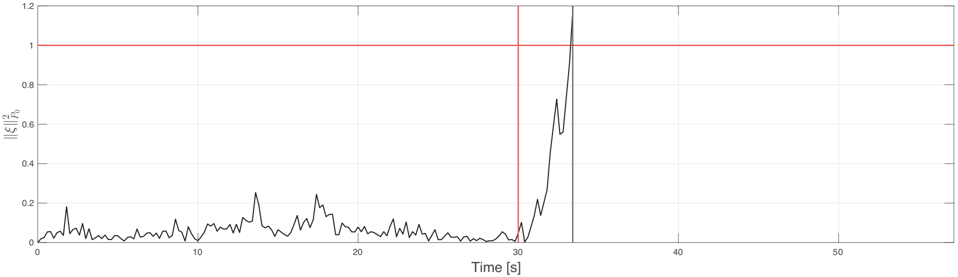
No false alarms were detected in any of the simulations perfomed.

Faulted case - actuator fault

A malfunction of the locomotion system was simulated: One of the tracks suffers a mechanical fault that changes its rotational speed.



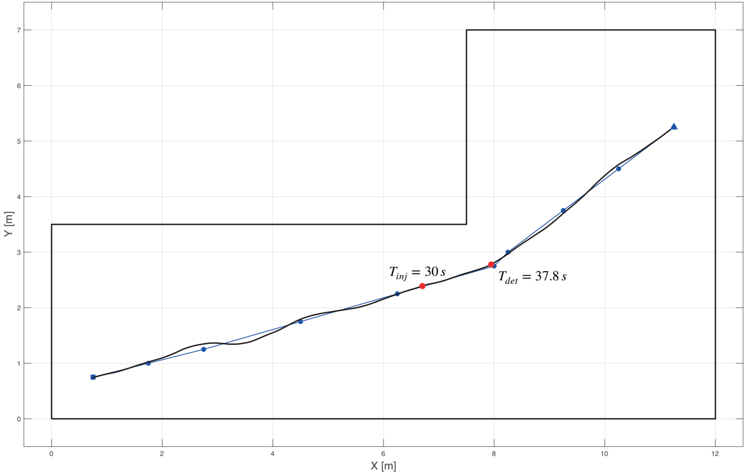
Faulted case - actuator fault



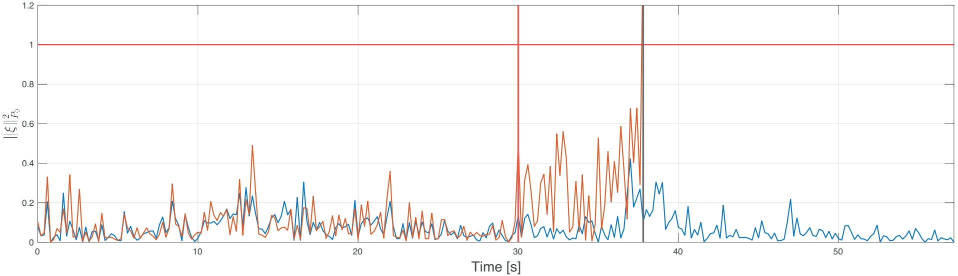
- The red solid vertical line represents the time of fault injection $T_{inj} = 30\,[s]$.
- The black solid vertical line represents the time of fault detection $T_{det} = 33.27\,[s]$.
- Fault is not recoverable, the robot's ability to move is impaired
- The robot is stopped at the time of detection

Faulted case - sensor fault

A drift of 0.05 $[m/s]$ in the forward velocity measurements recorded by an INS is considered.



Faulted case - sensor fault



- The quadratic function $\|\xi\|^2_{P_0}$, which was calculated for the faulty INS, is highlighted in orange. In light blue the value calculated for the healthy INS.
- The red solid vertical line represents the fault injection time $T_{inj} = 30\,[s]$. The black solid vertical line represents the time of fault detection $T_{det} = 37.8\,[s]$.
- The sensor fault is properly isolated and the robot continues to move along the prescribed trajectory based on healthy measurements

Conclusions

- This paper proposes a solution to the problem of detecting faults that affect the capability of a skid-steered tracked mobile robot to follow an assigned trajectory.
- A set-based approach was used to define a threshold logic capable of detecting, in real time, faults that could affect the robot's sensors and actuators
- The proposed FDI algorithm can be easily implemented on low-capacity embedded platforms.
- To show the effectiveness of the proposed algorithm, some numerical simulations were performed

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