Online fault diagnosis of complex dynamical systems: complementarity of model-based and data-driven methods. Application on eco-designed soft manipulators

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Abstract

The evolution of robots from rigid structures to soft and deformable entities has transformed their applications, particularly in fields such as healthcare and exploration [2, 8]. Soft robots, often inspired by biological systems, offer unprecedented versatility and adaptability enabling many tasks previously inaccessible to traditional rigid robots. However, this flexibility introduces challenges, particularly in understanding and managing internal faults like plasticity. Plasticity, also known as plastic deformation, is the ability of a solid material to undergo a permanent deformation — that is, an irreversible change in shape — when subjected to a given force. The effect of plasticity occurrence is that the material does not return to its initial resting shape when no force is applied. This aspect of how this kind of internal fault can occur or evolve in soft robots is quite not well known and understood. Despite extensive work on modeling, design, planning and control, fault diagnosis in soft robots remains underexplored, with most existing work focusing on generic faults such as sensor or actuator faults for which classical approaches exist as for rigid robots [1, 6, 5]. However, phenomenon such as plasticity is not addressed in literature to the best of our knowledge. The objective of my thesis is to develop the methods to detect and characterize plasticity for soft robots.

The classical approach for fault diagnosis relies on a system model that is sufficiently simple and manipulable to derive Analytical Redundancy Relations (ARR) or observers, such as by generating residuals based on classical state-space representations. These residuals are then evaluated using data from the real physical system to detect or identify faults. However, as the system becomes more complex—featuring a large number of states and partial derivatives with respect to multiple variables—this model-based approach becomes impractical. Soft robots are such systems which pose unique challenges due to their complex dynamics and mechanical properties [7]. Most classical fault diagnosis methods based on accurate analytical models [3], are difficult to apply to soft robots, while data-driven approaches [4], struggle to capture the underlying physics

which is useful to evaluate the effect of the fault and depend heavily on the availability of faulty data is often scarce in real-world systems. Plasticity is a phenomenon which is dependent on the internal strain which accumulates locally within the material. In order to overcome the above two challenges and perform soft robot diagnosis, particularly for plasticity, we need a method which can give useful information about strains at the level of material. Reduced Order Models (ROMs) consider certain assumptions to evaluate the internal strain and may fail to give precise information in certain scenarios. To evaluate these internal strains, a high-fidelity simulation based on a full-order FEM (Finite Element Method) model is a preferred choice, which eliminates the need to derive and compute strain analytically.

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