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A model-based approach to robot fault diagnosis

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Abstract

This paper presents a model-based approach to online robotic fault diagnosis: First Priority Diagnostic Engine (FPDE). The first principle of FPDE is that a robot is assumed to work well as long as its key variables are within an acceptable range. FPDE consists of four modules: the bounds generator, interval filter, component-based fault reasoner (core of FPDE) and fault reaction. The bounds generator calculates bounds of robot parameters based on interval computation and manufacturing standards. The interval filter provides characteristic values in each predetermined interval to denote corresponding faults. The core of FPDE carries out a two-stage diagnostic process: first it detects whether a robot is faulty by checking the relevant parameters of its end-effector, if a fault is detected it then narrows down the fault at the component level. FPDE can identify single and multiple faults by the introduction of characteristic values. Fault reaction provides an interface to invoke emergency operation or tolerant control, even possibly system reconfiguration. The paper ends with a presentation of simulation results and discussion of a case study.

Keywords: Fault diagnosis; Model-based reasoning; Robotics

1. Introduction

The problem of robotic diagnosis and fault tolerance presents a considerable challenge to both the artificial intelligence and robotics research communities [1,2].

Many contributions have been made to this topic in the past two decades [3–5]. For example, Visinsky et al. [6] provided a layered fault tolerance framework, for remote robots, consisting of servo, interface and supervisor layers. The layers form a hierarchy of fault tolerance which provide different levels of detection and tolerance capabilities for structurally diverse robots. Schroder [7] proposed a qualitative approach to fault diagnosis of dynamical systems, mainly process control systems. However, most of current fault diagnosis approaches focus on one of robot fault categories, hardware failure, or faults caused by modelling errors or uncertainty.

This paper proposes the First Priority Diagnostic Engine, FPDE, as a means to diagnose robot faults from the viewpoint of composite data streams of robotic key variables. The FPDE approach recategorizes robot faults into sensor faults, robotic behaviour faults and modelling errors. Sensor faults can be diagnosed by low-level sensor diagnosis. A robotic behaviour faults are composed of orientation faults and translational faults. The behaviour fault could be caused by hardware failures, e.g. a gearbox fault, excluding sensory fault, and uncertainty factors. Uncertain motion collision can lead to orientation faults and/or translational faults. The FPDE first diagnoses predetermined key priority variables only (e.g. position of an end-effector); a robot is assumed to have no fault if the key priority variables are within acceptable bounds; otherwise it goes to diagnose its variables at a lower level. An interval filter is introduced to deal with noise from measurements. The FPDE deals with a large degree of noise produced from payload changes, by simply ignoring false faults in the time interval of gripper action. Once a fault is detected, characteristic values automatically isolate the fault position. The characteristic mapping presents the relation between the inputs and outputs of a physical system using characteristic values, which are quantities extracted from the quantitative intervals of a domain in order to describe the corresponding qualitative information, for diagnostic purposes. Hence, the FPDE can be applied to general

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Notation

$\hat{\theta}_i$, $\dot{\hat{\theta}}_i$	*i*th estimated orientation angle and its velocity.
Θ_d, $\dot{\Theta}_\mathrm{d}$	desired joint trajectory and its velocity of a robot.
Θ_b, $\dot{\Theta}_\mathrm{b}$	bounds of a joint trajectory and its velocity.
Θ_offset	joint repeatability.
Θ_s, $\dot{\Theta}_\mathrm{s}$	joint trajectory from sensors and its velocity.
$\Theta^{\pm}$	upper and lower trajectory bounds based on a kinematic model.
$\tilde{\Theta}^{\pm}$	upper and lower trajectory bounds based on a dynamic model.
$\hat{\Theta}_\mathrm{b}$, $\dot{\hat{\Theta}}_\mathrm{b}$	estimated bounds of a joint trajectory and its velocity
$\hat{\Theta}_\mathrm{s}$, $\dot{\hat{\Theta}}_\mathrm{s}$	estimated joint trajectory and its joint speed
$\hat{\Theta}_i$, $\dot{\hat{\Theta}}_i$	*i*th estimated joint trajectory and velocity, respectively
τ	computed torque of a robot
CI_i	time instant of a characteristic value of a position interval in the *i*-coordinate
CV_j	characteristic value of a position interval in the *j*-coordinate
CI_{iv}	time instant of a characteristic value of a velocity interval in the *i*-coordinate
CV_{jv}	characteristic value of a velocity interval in the *j* coordinate
J_i	joint fault for the *i* coordinate
$\hat{l}_i$	estimated length of the *i*th link.
$\hat{X}$, $\hat{Y}$	estimated position of an end-effector in *x*-, *y*-coordinates
$\dot{\hat{X}}$, $\dot{\hat{Y}}$	estimated speed of an end-effector in *x*-, *y*-coordinates

dynamical systems independent by their control systems design. This approach can diagnose both sensor-based parameters and non-sensor-based.

In Section 2, we present the problem formulation for robot fault diagnosis and a robotic diagnosis system. In Section 3, we describe the FPDE approach, and in Section 4, we give a case study based on the simplified robot arm of the Beagle 2 Lander, finally conclusions are presented.

2. Problem formulation and solution

This section introduces an interval-computation based description for robotic faults, and proposes a model-based reasoning solution to the problem.

2.1. Robotic fault description

Generally speaking, there are two types of parameter in robotic diagnosis, sensor-based parameters and non-sensor-based parameters. The latter usually can be mathematically described by the former. Let us use capital letters to describe variables that are not necessarily uniquely determined by our knowledge, i.e. that can take values from an interval. In these terms, if a measurement leads us to a conclusion that the value of this variable belongs to an interval $[\theta^-_{\Delta t_i}, \theta^+_{\Delta t_i}]$, then we can express this knowledge as: $(\theta^-_{\Delta t_i} \le \Theta_{\Delta t_i} \le \theta^+_{\Delta t_i})$. This means there is no fault for variable $\Theta_{\Delta t_i}$, otherwise a fault is detected. In these terms, the basic problem of fault diagnosis for a *n*-link robot can be reformulated into the following two steps:

- For sensor based parameters (e.g. $\Theta_{\Delta t_i}$), to check whether the following formula is true provided $\Theta_{\Delta t_i}$:

$$\forall \Theta_{\Delta t_i}, \quad (\Theta_{\Delta t_i} \in [\theta^-_{\Delta t_i}, \theta^+_{\Delta t_i}]) \tag{1}$$

- For non-sensor based parameters (e.g. $Y_{\Delta t_i}$), to check whether the following formula is true provided $\theta^-_{\Delta t_i}$, $\theta^+_{\Delta t_i}$ and $y^-_{\Delta t_i}$, $y^+_{\Delta t_i}$

$$\forall \Theta_{\Delta t_i} \in [\theta^-_{\Delta t_i}, \theta^+_{\Delta t_i}], \quad \exists f_m(\Theta^1_{\Delta t_i}, \ldots, \Theta^m_{\Delta t_i}) \in [y^-_{\Delta t_i}, y^+_{\Delta t_i}] \tag{2}$$

where $i=1,2,\ldots,n$ stand for *n* sensor-based parameters, e.g. orientation angles from robotic sensors, $j=1,2,\ldots,m$ stand for *m* non-sensor-based parameters, e.g. position of an end-effector.

Actually by checking the validity of these formulas, we can check whether both sensor based and non-sensor based parameters are within their bounds. If all parameters meet the above bounds requirement, it means that the *n*-link robot works in an acceptable manner, otherwise a fault has been detected, based on which further diagnosis should be carried out.

2.2. Robot diagnosis system

A robot diagnosis system, depicted schematically in Fig. 1, is proposed as a solution to the problem of robotic faults. The structure consists of three parts: the robotic system, motion planner and robotic fault reasoning: the FPDE. The robotic system could be a kinematics-based or dynamics-based system, which usually includes physical robots, sensors and motion control unit. The motion planner is used to plan robot motion to meet the task requirements. It generates the desired data (e.g. Θ_d, $\dot{\Theta}_d$ and τ) for both the motion control unit and fault diagnosis. The motion planner is usually packaged with the robot by the robot provider or