Control Engineering Practice 37 (2015) 80–88

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Cascade force control for autonomous beating heart motion compensation

Michel Dominici *, Rui Cortesão

Institute of Systems and Robotics, University of Coimbra, Portugal

ARTICLE INFO

Article history:
Received 5 May 2014
Accepted 18 December 2014
Available online 11 February 2015

Keywords:
Autonomous motion compensation
Force control
Model predictive control (MPC)
Kalman active observer (AOB)
Beating heart surgery

ABSTRACT

Robotic-assisted heart surgeries do not allow autonomous compensation of cardiac motion. This paper tackles this problem, based on a robotic control architecture that relies on force feedback, without requiring vision data. The algorithm merges two cascade loops. The inner one is based on the Kalman active observer (AOB) for model-reference adaptive control and the outer one based on a model predictive control (MPC) approach generates control references for beating heart motion compensation. A 4-DoF surgical robot generates desired surgical forces and a 3-DoF robot equipped with an *ex vivo* heart at the end-effector reproduces realistic heart motion.

1. Introduction

Cardiovascular diseases are the first cause of mortality in the world. More than 17 million people die every year, representing 29% of all global deaths. Among these, coronary heart diseases are the most critical ones, reaching up to 7.2 million deaths (WHO, 2009). The coronary artery bypass grafting (CABG) is the most common surgical intervention to reduce the risk of death. Currently, the CABG procedure involves a median sternotomy (a 16–20 cm incision in the thorax allowing a direct access to the heart) and a cardiopulmonary bypass (CPB), where heart and lung functionalities are performed by an extracorporal machine. Significant trauma and infection risks due to the long duration of surgery are the major downsides of the sternotomy approach (Klesius et al., 2004; Newman et al., 1991). But the greatest source of complications and post-operatory mortality for patients is due to the CPB. Problems such as inflammatory blood response to the heart–lung machine, the risk of microemboly, kidney dysfunctions and neurological complications such as stroke during the clamping of the aorta have motivated new solutions that circumvent the use of extracorporal circulation (Eagle & Guyton, 2004). Passive mechanical stabilizers have been conceived for locally decreasing heart motion, allowing direct surgical procedures on the beating heart. Placed around a region of interest (e.g., coronary artery), these stabilizers constraint the motion by suction or pressure. Many improvements have been done over the years, although considerable residual heart motion (1–1.5 mm) still remains (Lemma, Mangini, Redaelli, & Acocella, 2005). Additionally, the intense pressure necessary to cancel out heart motion affects blood circulation. Sucker-type stabilizers do not present this problem but they introduce vacuum pressure that can cause epicardial damage (Dzwonczyk, del Rio, Sun, Michler, & Howie, 2005). This paper proposes a force control architecture for robotic-assisted heart surgery with autonomous heart motion compensation.

The paper is organized as follows. Related work mainly in the area of beating heart surgery is addressed in Section 2. The goal of this paper is highlighted in Section 3, which consists of designing and testing a cascade MPC–AOB robot control architecture for autonomous heart motion compensation, relying on force data. The overall cascade MPC–AOB architecture is presented in Section 4 where an AOB inner loop guarantees a well defined stable plant and a MPC outer loop compensates force disturbances induced by heart motion. Experimental results with a time varying surgical force reference are presented in Section 5. Finally, Section 6 concludes the paper.

2. Related work

Compensating physiological motion autonomously through sensory data (e.g., vision and/or force) enables comfortable surgery without the drawbacks of classical procedures, powering and enhancing surgical dexterity. Based on visual servoing, Nakamura and Kishi (2001) have proposed high speed cameras to track movements of target points on the heart, providing autonomous robot motion synchronization. Using also a high speed vision system, Ginhoux et al. (2005) proposed a motion canceling algorithm based on a MPC

* Corresponding author.
E-mail addresses: michel.dominici@gmail.com (M. Dominici), cortesao@isr.uc.pt (R. Cortesão).

http://dx.doi.org/10.1016/j.conengprac.2014.12.012
0967-0661/

approach where future heart motion is predicted. This approach assumes that the heartbeat rate stays constant. More recently, Bachta, Renaud, Laroche, Forgione, and Gangloff (2008, 2011) improved classical stabilizer solutions with piezo-electrical actuation for a 1 DoF system. Using vision data, H_∞, feedback control with notch filter and MPC are assessed through *in vivo* experiments, requiring prior knowledge of heart motion. Solutions only based on visual servoing present several drawbacks (Richa, Bó, & Poignet, 2010). Surgeries are performed in a cluttered environment where medical instruments can occlude artificial and natural landmarks. This situation entails tracking problems and disturbing motion compensation. Moreover, contact tasks (e.g., suturing, incision and ablation) locally deform soft tissues, affecting landmark calibration. Another important point is that during contact tasks, physiological motion induces disturbance forces which can hardly be compensated by vision information.

Control architectures based on force feedback do not suffer from these drawbacks and can give haptic feedback to surgeons, which is an indispensable feature for surgical telemanipulation, in particular for operations with delicate suture material (Kitagawa, Okamura, Bethea, & Gott, 2002; Okamura, 2004; Wagner, Stylopoulos, Jackson, & Howe, 2007). However, these architectures have to deal with higher sensor noise (e.g., for low contact forces, the noise is often bigger than the signal) and no physiological motion information can be obtained before contact. Cagneau, Zemiti, Bellot, and Morel (2007) have proposed a force feedback control scheme to compensate the periodic motion of organs. Iterative learning control was implemented as an outer loop to reject periodic disturbances, reducing bad transients during the learning phase. No specific model is necessary for the robot and environment, although the period of the perturbation needs to be known in advance. This assumption is problematic for cardiac surgeries due to random and chaotic nature of heart motion (Nakamura et al., 2001). Cortesão and Poignet (2009) have proposed two independent AOBs for force control and motion compensation. The first AOB is responsible for model-reference adaptive control to guarantee a desired closed loop dynamics for the force. The second one performs control actions to compensate physiological motion. Simulation results have shown high quality compensation capabilities. Zarrouk, Chemori, and Poignet (2013) proposed a PID force control solution to compensate a 0.125 Hz sinusoidal motion in 1-DoF. More recently, Kesner and Howe (2014) presented a catheter robotic system dedicated to beating heart surgery. A home made 1-DoF distal force sensor provides force feedback information. Additionally, a force-modulated position controller with friction and dead zone compensation was developed to apply a constant force on the mitral valve. Based on observations of previous cardiac motion cycles, a predictive auto-regressive filter estimates the desired catheter acceleration, which is added to the control loop as a feedforward term. The results showed good capability to maintain in one direction a constant force on a fast moving target, although catheter-based solutions have a limited force range. Dominici, Cortesão, and Sousa (2011) presented a comparative study of two force control architectures for physiological motion compensation. The first one based on a MPC approach uses a mathematical model to predict system behavior (Dominici, Poignet, & Dombre, 2008). The second one is based on an AOB to impose desired closed-loop dynamics (Cortesão, 2007). The performance of both controllers has been evaluated for constant force references. MPC and AOB have shown good motion compensation capabilities, although residual force amplitudes were still high to consider these architectures without improvements. Therefore, this paper aims to merge both MPC and AOB control architectures to achieve better results.

Using other sensing information, Gagne, Laroche, Piccin, and Gangloff (2012) developed a mechanical system to couple with a classical stabilizer based on gyroscopic actuation, accelerometer and optical sensing. *In vivo* experiments proved the feasibility of the solution to reduce residual heart motion in one direction. They used an adaptive control which requires knowledge of the fundamental cardiac frequency. This system does not cancel breathing motion, though.

3. Goal

The goal of this paper is to implement a force control architecture to compensate 3D disturbances due to cardiac and breathing motion, while tracking time varying surgical force references. The challenge is to use no *a priori* information about these disturbances, relying the control actions on measured forces and on a generic/simple contact model. To accomplish this, a cascade control architecture is investigated merging MPC and AOB techniques. A Heartbox robot equipped with an *ex vivo* heart reproduces heart motion and a medical robot generates desired surgical forces on the moving heart. The force reference is artificially generated, incorporating time varying and low frequency signals which are typical in surgical tasks. The Heartbox motion generates force disturbances on the medical robot, which should be compensated by the control architecture. Therefore, the goal is to achieve high quality beating heart motion compensation based on force feedback, without knowing in advance cardiac motion, guaranteeing also surgical force tracking with high performance.

4. Cascade MPC–AOB control architecture

The MPC approach presented in Dominici, Poignet, Cortesão, Dombre, and Tempier (2009) is applied to an unstable system. Even if MPC can deal with such plant, a stable plant is more robust to handle external disturbances (such as heart motion). Therefore the classical MPC approach is merged with the AOB design, described in Cortesão (2007), into two cascade loops as shown in Fig. 1. An AOB

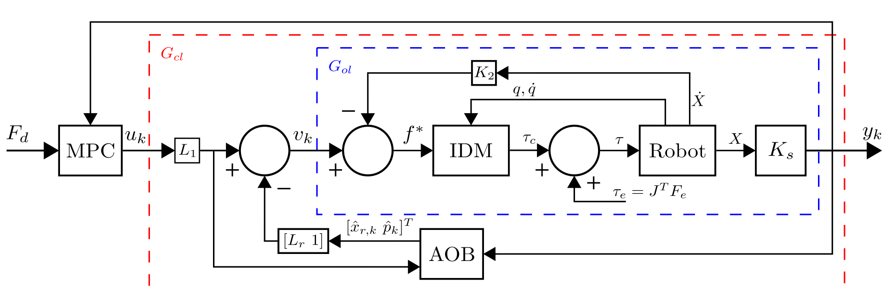

Fig. 1. Cascade MPC–AOB force control architecture for beating heart surgery. Computed torque techniques linked with the robot inverse dynamic model (IDM) generate a decoupled and linearized system. The open loop transfer function G_{ol} also takes into account a damping factor K_2 and the environment stiffness K_s. The desired closed loop transfer function G_{cl} is obtained by the AOB architecture using the state-feedback gain L_r and the extra state $\hat{p}_k$. L_1 is the first element of L_r. The MPC generates a processed reference force u_k for AOB control, based on the desired force F_d, the measured force y_k and G_{cl}. The external torque τ_e is mainly due to beating heart disturbances.