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Robust decentralised control of a hydrodynamic human circulatory system simulator

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ABSTRACT

A novel feedback controlled hydrodynamic human circulatory system simulator, well-suited for in-vitro validation of cardiac assist devices, is presented in this paper. The cardiovascular system simulator consists of high-bandwidth actuators allowing a high precision hardware-in-the-loop hydrodynamic interface in connection with physiological circulatory models calculated in real-time. The hydrodynamically coupled process dynamics consist of several actuator loops and demand a multivariable control design approach in the face of system nonlinearities and uncertainties. Based on a detailed model employing the Lagrange formalism, a robust decentralised controller is designed. Fixed structural constraints and the minimisation of the $\mathcal{H}_\infty$-norm necessitate the application of nonsmooth optimisation techniques. The robust decentralised norm-optimal controller is tested in extensive in-vitro experiments and shows good performance with regard to reference tracking and system coupling. In-vitro experiments include multivariable reference step tests and frequency analysis tests of the vascular impedance transfer function.

1. Introduction

Cardiac insufficiency is among the most common causes of death in industrialised countries. Approximately 10 million cases of cardiac insufficiency are estimated to exist in Europe and it is the number three cause of death for the overall German population and number two for the female German population [14]. Despite continuous advances in clinical therapy, drug medication, and biomedical technology, the treatment of cardiac insufficiency remains one of the major medical challenges. In cases of severe reduction of cardiac output, mechanical support or replacement with a donor heart might be indicated. These therapeutical measures become inevitable, if conventional drug therapy is no longer sufficient. For this application, heart circulatory mechanical assist technology has been developed and is available as ventricular assist devices (VAD) or total artificial hearts (TAH). The application of VADs or TAHs has been established for different clinical scenarios. For example in "bridge to bridge" a VAD is used to temporarily support the left and/or right heart's pumping function until a final decision for further therapy is made, where in contrast to that in "bridge to recovery" temporary support with the objective of heart recovery is provided. In "bridge to transplant" the heart is supported until a donor heart is available and "destination therapy" is applied if there is no option to obtain a donor heart [8]. Depending on the intended use, the requirements for VADs and TAHs vary. VADs typically support the left and right heart by taking blood from the atrium or the ventricle and ejecting it into the aorta or pulmonary artery. A TAH is a complete replacement of the heart and thus takes over its functionality.

All mechanical circulatory support devices, whether designed for intra- or extracorporeal use, have to be validated in in-vitro and in-vivo experiments prior to the application in a human patient. This applies in particular to feedback controlled VADs or TAHs, which are highly safety critical. Therefore, in-vivo tests are usually conducted with animal models. One of the main disadvantages of such procedures, besides being time-consuming, cost-intensive and not reproducible is using an animal as a test platform. As an alternative, hydrodynamic circulatory system simulators, or mock circulatory loops (MCL), were developed to validate VADs or TAHs before application in an animal or clinical scenario. The first MCLs were designed with the requirement to dynamically simulate the human circulatory system, as if seen from the

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1746-8094/

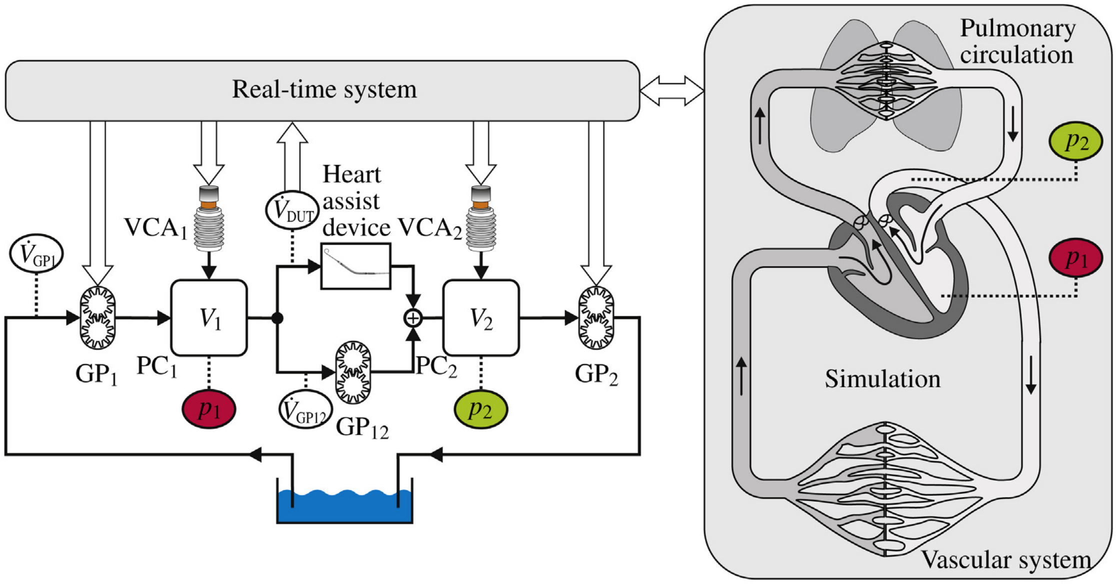

Fig. 1. Hydrodynamic system simulator (left) coupled to the circulatory system simulation (right), where in this example the left ventricle chamber pressure p_1 (pre-load) and the pressure in the aortic arch p_2 (after-load) are calculated by the simulation and are used as reference values for MCL control (PC: pressure compartment). Measured values in the experimental setup are indicated by ellipsoids.

hydraulic impedance transfer function from the heart [11]. The human circulatory system is divided into different compartments, corresponding to ventricles, vascular segments or branches. In MCLs, lumped parameter vascular segments or branches are commonly implemented as hydraulic elements: electro-mechanical pinch valves (flow resistance), pressurised air chambers (vascular compliance), or back-pressure valves (heart valve) [12]. The resulting MCLs are often complicated and, although in sometimes computer-controlled, often not able to precisely simulate the dynamic pressure during ventricular contraction or orthostatic reactions [15]. A trend to include physiological models interacting with MCLs can be observed in the last years leading to hybrid MCLs [10].

The principal disadvantage of common MCLs are pneumatically driven air chambers, which have several adverse effects, like leakage, nonlinearity, disturbances on adjustment, and slow parameter adaption. New designs, for example [3], therefore consider the simulation of ventricular contraction with feedback controlled high bandwidth voice coil actuators. In the described MCL, the elastance of the heart is continuously adapted using computer-controlled bellows pumps, connected to a closed hydraulic system. In contrast to that [4] present a MCL based on a fluidic operational amplifier based on a gear-pump output stage. The gear pumps are controlled in order to simulate the impedance of the corresponding active/passive components of conventional MCL. Common to all approaches is a design that is based on hydraulic components and valves to simulate the circulatory dynamics and the heart valves, respectively. However, in modern MCL approaches several aspects of circulation (semi-hybrid) or the full circulation (hybrid) are substituted by a model [10]. In case of the hybrid MCL only a hydraulic interface is needed in combination with a detailed simulation.

In this contribution we present an approach based on high bandwidth stiffly coupled voice coil actuators connected to metal bellows and gear pumps. We developed a new MCL that is based on a hardware-in-the-loop (HIL) design idea [6]. The pressure compartments of the MCL are connected to a numerical real-time simulation and have to rely on fast and robust feedback pressure control. Since the actuators and sensors of a compartment represent a multivariable coupled system, we design a robust decentralised controller and an implementation approach with regard to nonlinearities like actuator windup.

This paper is organised as follows. Section 2 describes the design of the HIL-MCL for which the dynamic plant model is derived in Section 3. The controller design is presented in Section 4 and the results of an experimental study are given in Section 5. Finally, this paper ends with a conclusion and a discussion.

2. Hydrodynamic circulatory system simulator

The basic concept of the hydrodynamic circulatory system simulator is a strict separation between dynamic models of the heart or the vascular system and the compartments of the MCL. Heart and vascular system are assigned left and right pressure compartments in the MCL, respectively. An overview of the MCL coupled to the physiological system simulation is given in Fig. 1. The MCL compartments serve as hydraulic interface with the intention of simulating the physiological compartment to which the VAD or the TAH is coupled to. Examples for these compartments can be the left ventricle and the ascending aortic arch. In Fig. 1, the typical setup of two pressure chambers is shown, which is actuated by three gear pumps and two voice coil actuators/metal bellows pumps. A simulation is run in real-time that serves as a reference trajectory generator for compartmental pressures. Nonlinear effects on the compartmental pressure, for example the ventricular contraction, can be successfully calculated in the system simulation. A detailed and fast adaption of VAD's pre- and afterload can be achieved via real-time computer simulation driving the high bandwidth actuators with a feedback control-loop. Cardiac assist device tests with HIL-support can be given to right or left heart VAD or TAH which can be autonomously operated using their driving console. The operation of the VAD or TAH is measured in terms of flow through the VAD "$\dot{V}_{VAD}$" and fed back to the simulation).

Fig. 2(a) shows the integrated MCL with two pressure compartments. Each compartment is extended with a gear pump and a combination of a voice coil actuator (VCA) and a metal bellows pump, attached to the corresponding compartment. The compartments are made out of acrylic glass, containing ports for the VCA and the bellows pump. Both chambers in Fig. 2(a) represent independent modules. In addition to the two gear pumps, a third