An Autoregulation Unit for enabling adaptive control of sensorized left ventricular assist device

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***Abstract*— This paper describes an integrated system for facing heart failures (HF) in an innovative way. Existing left ventricular assist devices (LVAD or VAD) are usually devoted to blood pumping without the possibility to adapt the speed to patient conditions during everyday activities. This is essentially due to the lack of sensorization, bulkiness, and the need of relying on device-specific controllers with reduced computing ability for the existing ventricular assist systems. In this work, an innovative integrated and portable device, the ARU, is presented for enhancing VADs applicability as a long-term solution to HF. The ARU is an universal device able to fulfill with the needs of sensorized VADs in terms of data storing, continuous monitoring, autoregulation and adaptation to patient condition changes during daily activities. The ARU is able to wirelessly interface wearable devices for offering additional monitoring features from remote. The ARU functionalities on bench have been tested by the interfacing with a sensorized VAD platform in order to prove the feasibility of the approach. Experiments of local and remote VAD speed changes and autoregulation algorithms have been successfully tested showing response time of 1 s.**

I. Introduction

As reported to the International Society of Heart and Lung Transplantation registry, the number of heart transplants has been 3500-4000 annually worldwide. However this number has not been increased over the last twenty years. This is due principally because of the limited availability of donors despite the growing number of patients with HF.

Although heart transplantation remains the gold standard, this imbalance between the supply of donor hearts and the demand of patients who suffer from HF has led to increased the use of LVADs or VADs as a longer term destination therapy, therefore not only as bridge to myocardial recovery or to heart transplantation [1][2].

Since the first introduction of a ventricular assist device (VAD), in 1963 by DeBakey [3], a variety of circulatory support devices has been developed [4-5]. The first examples, belonging to the pulsatile-flow VAD class, see the major players in: Abiomed (Abiomed, Inc., Danvers, Massachusetts, USA), Thoratec (Thoratec Corporation, Pleasanton, CA, USA), Novacor (Novacor, Rueil-Malmaison, France) and Heartmate (Thoratec Corporation, Pleasanton, CA, USA) [6-7].

Further improvements occurred with the design of continuous-flow LVADs that represent a large step forward in terms of durability and survival time. Indeed, these pumps show several advantages in comparison to the pulsatile ones being smaller in size, more quiet, simpler in design and construction and, above all, easier to be implant [8-9]. At present, continuous- flow LVADs are used for the treatment of patients with severe heart failure accompanied by shock and multiple organ dysfunction with the prospect of future heart transplantation [14]. Several continuous-flow devices have been tested and/or marketed to be used as a bridge to transplant (e.g. Debakey [10], Jarvik [11], Ventrasist [12], and most recently the Heartware HVAD [13]).

Considering all these aspects and the goal of a long- term therapy, which is the avoidance or the reduction of patient dependence on clinical management allowing him/her to return home, the implementation of an automatic, robust and adaptive physiological control strategy able to fast adjust pump output according to real patient status is mandatory. The current methodology to control the flow rate generated by continuous flow VADs implies a manual adjustment of the pump rpm (revolutions per minute) or flow by physicians. A revolutionary approach to reach a fully autonomous control could be the implementation of a continuous monitoring strategy with the purpose to optimize and personalize the heart unloading degree.

In this framework, this paper presents an integrated and portable device, named autoregulation unit (ARU), based on an innovative control strategy for sensorized LVADs. The ARU is able to automatically respond to physiological cardiac demand by a feedback mechanism which is directly based upon physic/physiological parameters. Furthermore, the ARU communicates with the external environment thanks to a Bluetooth module embedded on the device. Thus, it acts as a data-bridge towards tablet and pc, dedicated for the monitoring of implanted patients. and for accessing the ARU both from patient's and specialist's sides, according to preset patient-specific priorities and restrictions. The ARU can be also wirelessly interfaced to different wearable devices in order to improve the overall number of sensors.

A sensorized on-bench platform for sensing and monitoring the LVAD was exploited, in order to investigate the control feasibility and applicability of the ARU for a more precise patient monitoring.

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II. Material and Methods

A. System overview

In the devised scenario of an adaptive control of a sensorized VAD, there are essential characteristics to be considered during the design phase. These are mainly related to the flexibility, the portability, robustness and safety of the overall system (contributing to a deep revolution in the development of sensorized autonomous systems for new therapeutic approaches). These systems are based on new generation VADs with embedded sensors and dedicated unit for autoregulation. The autoregulation control unit proposed in this paper is a dedicated board including many functionalities, such as remote monitoring and control of the VAD, storing of physiological and physics parameters, and autoregulation.

During the design, the ARU has been designed with the final aim of interfacing any existing VADs to make the proposed system universal. In order to fit this requirement, the hardware design of the ARU has been carried by the integration of standard interfaces, such as serial and standard Bluetooth ports by implementing a series of general rules and control actions to be performed. These peripherals are managed by a dedicated FPGA controller, in order to allow to interface any device through the development of specific firmware with no changes in the hardware. This indeed makes the ARU a flexible and universal system. In this work, the operation of the ARU will be demonstrated by interfacing a continuous flow pump from CircuLite (Aachen, Germany). In addition, the ARU should be miniaturizable in order to allow the portability of the system since it is based on standard electronic components. The dimension reduction down to 139 mm x 94 mm is trivial and linked to the definition of the final implemented functionalities and connections.

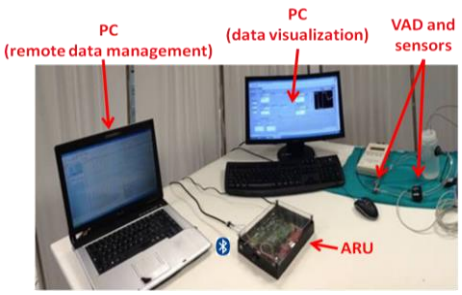

Figure 1. On bench platform for the operation of the sensorized VAD in a simulated scenario for the demonstration of ARU functionalities.

The ARU is the brain unit of the monitoring system. In fact, thanks to its connections with the sensorized VAD and others modules (i.e. wearable monitoring interfaces for the real-time acquisition of physiological parameters), it is able to manage incoming data and store them on the internal available memories. In particular, all parameters are monitored by the LVAD-embedded flow and pressure sensors, which continuously collect data. The ARU can control the VAD by sending dedicated commands for changing the speed, or stop and enable the pump. These functionalities can be activated both through a dedicated unit control interface (UCI) and remotely via a Bluetooth link. Moreover, the UCI unit can display important physic/physiological data of the sensorized LVADs in real-time. In addition, the ARU is able to perform autoregulation of the pump speed autonomously while the system is worn by the patient. Two types of autoregulation algorithms have been implemented in the ARU, exploiting proportional-integrative and threshold control methods on flow and pressure respectively. It is worth noting that further algorithms can be implemented on the same device on the base of medical needs. A pc for data visualization during the research work is used for allowing data visualization.

B. Implementation of a sensorized on bench platform

In order to demonstrate the feasibility of the system in a working scenario, a sensorized VAD platform (i.e. the on bench platform) has been set up and used during the experimental evaluation. The on bench platform has been assembled to simulate the functions of the sensorized VAD and it is shown in Fig. 1.

The core of the on bench platform is the Synergy™ Device, a VAD pump provided by CircuLite (Aachen, Germany), which is able to provide up to 4.25 liters of blood-flow per minute. The Synergy™ Device is equipped with a wired electronic controller to switch on and off the pump and allows a manual setting of the motor speed. In the setup, the device was fastened to an homemade hydraulic circuit made by a silicone tube, 3/8 x 1/16" inches (about 9.5 mm x 1.5 mm) (Internal Diameter x Wall Thickness) in size, connected to a tank filled with the fluid to be pumped into the flow loop. The fluid contained the 48.3 percent of glycerine and the 51.7 percent of water to simulate the viscosity of blood and to avoid the bearings damage of the pump. Commercially available sensors have been also integrated in the platform. Two Mikro-Tip® Pressure Catheters (SPR-350S, Millar Instruments, Houston, USA) were settled in input and output of the pump, because of their compatibility for the measurements of pressure on large animals (Dog/Pig/Ship). Indeed, the piezoresistive sensor located at the tip of the catheter, provides optimal data for monitoring high-fidelity cardiovascular pressures at the source. As reported in the datasheet, it presents high linearity and sensitivity (up to 5 μV/V/mmHg) and is able to measure a pressure ranging from -50 mmHg +300 mmHg (-6.7 to 40 KPa), which is an overestimation of the range of interest of this study (+90 to 120 mmHg). Sensors calibration has been performed before assembling the on bench platform. An ultrasonic flowmeter provided by em-tec (Finning, Germany) was integrated as well for blood flow measurement. It is a non-invasive clamp-on transducer based on the principle of the transit time difference from ultrasonic acoustic waves in up and downstream directions. It has an excellent accuracy and stability when used for flow measurement in Polyvinyl Chloride and silicone tubes. The transducer measures until to a maximum flow value of +10000 ml/min. This matches with the application requirements.

C. ARU hardware and firmware implementation

The embedded ARU, shown in Fig. 2, is made by two main boards: the first one is the FPGA development board, available off the shelf, and the other is a custom printed circuit board. System flexibility and efficiency is increased by the use of the FPGA, thus improving the overall

performance when multiple control tasks and algorithms are enabled at the same time.

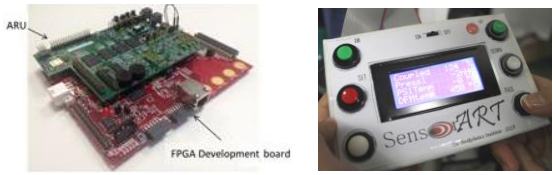

Figure 2. The ARU (Left) and the UCI (Right).

The ARU hardware is integrated in a single box, thus allowing the patient to easily wear it by means of a belt. It is supplied by a commercial battery and the overall device fits in a boundary box of 170 mm x 135 mm x 45 mm and it is about 350 g in weight. This dimensions are fully miniaturizable down to 139 mm x 94 mm. The firmware implemented on the FPGA manages all the system from a software viewpoint. It includes and manages the functionalities of memories management, Bluetooth interface communication towards monitoring devices (such as PCs and tablets), serial communication to the sensorized LVAD, UART/BL interface to wearable portable devices for the acquisition of physiological parameters. The firmware is implemented in VHDL (VHSIC Hardware Description Language, where VHSIC is the acronym of Very High Speed Integrated Circuits) code to make the proposed system universal.

The UCI is part of the whole monitoring system and allows local control of the VAD in case of failure of the autoregulation device, thus improving the safety of the overall system. The UCI has been developed in order to visualize real-time data from the sensorized LVADs, to set the desired pump speed and allow the pump stop&go. In section III, the results of the control speed by the UCI are reported. The UCI unit is based on an LCD display and a set of push-buttons in order to provide the specialist an easy-to-use interface, just as traditional (and medical accepted) VAD controllers. The interface between the ARU and the UCI is wired via a custom connector.

D. Autoregulation algorithms

One of the most relevant feature of the ARU is the possibility of implementing algorithms for adapting the VAD to the patient's physiological requirements and activity in real-time. The implemented algorithms are based on traditional control rules (e.g. PID controller) and dynamic data coming from the sensors. Safety is guaranteed by the alarms implemented at low level on the ARU itself, and by the alarms and thresholds set in the Pc or tablet by the specialist. As soon as they are out of specific ranges, the specialist is alerted and can modify the VAD parameters.

The ARU control algorithms implemented so far are:

- proportional-integrative (PI) control of the pump speed in order to achieve the desired flow value;
- control on the pressure variations, and eventually reset, with alert generation in case of fast and /or repetitive changes in the pressure value.

Of course, further algorithms can be implemented in future on the basis of physiological parameters. ARU control algorithms based on the desired flow value have been implemented and their effectiveness has been verified by the in vitro platform. In the final setup the pressure sensors were located at the input and the output of the pump at 1 mm distance, whereas the flowmeter was positioned at 15 cm distance downstream the pump. The ARU communicates with the hardware components composing the in vitro platform through serial communication lines and the National Instruments data acquisition (DAQ) board that will be part of the implanted wireless electronics of the VAD. Data acquired from the platform, such as pump speed, pump current, flow and pressure are managed by a dedicated pc connected to the ARU via a serial port, thus simulating data coming from the sensorized LVAD. Afterwards, all data are sent to the PC via Bluetooth connection for testing the wireless communication. In this way, it has been possible to test and online check the autoregulation algorithms as reported in the following.

1) Autoregulation to the desired flow level. In order to implement autoregulation, for every running cycle the ARU continuously controls pressure and flow values. In particular, as regards the flow control, the algorithm checks the current flow value coming from the pump is in line with the desired value. When different, the PI controller changes the speed for reaching the desired flow.
2) Autoregulation algorithms in case of suction events. In order to assess the performance of the algorithms for controlling the pressure variations at the inlet of the pump a further experimental session has been carried out. This algorithm has been implemented to make the ARU reacting to the suction events (i.e. inlet pressure beyond a threshold) by resetting the pump, aiming to recover the normal working condition.

III. RESULTS AND DISCUSSION

Specific experimental sessions have been performed to assess the capability of the ARU to manage the data coming from the on bench platform and the possibility of changing the VAD speed through the UCI and from remote. In addition, flow autoregulation and suction detection algorithms have been tested.

A. Pump speed control

In order to test the control of the pump speed through the ARU, the LVAD was activated and different levels of LVAD speed have been set. The speed of the pump has been changed both through the local controller and the remote PC in order to assess the potentialities of the ARU. Initially, the speed of the pump has been changed remotely through a dedicated PC for remote data management (as in Fig. 1) communicating with the ARU via Bluetooth. Afterwards, the speed of the pump has been changed through dedicated buttons of the local controller. In particular, the pump speed has been stepwise increased from 20000 to 26000 rpm and successively decreased from 26000 to 20000 rpm with step of 1000 rpm. The speed changes and the corresponding flow variations are showed in Fig. 3. The responsiveness of both the local and remote controllers is within 1 s, that is the typical time between two consecutive data packets sent from the VAD to the ARU.

B. *Autoregulation to the desired flow level*

These experiments were aimed at testing the flow control of LVAD in different conditions, by simulating the physiological variations that normally occur in VAD-implanted patients.

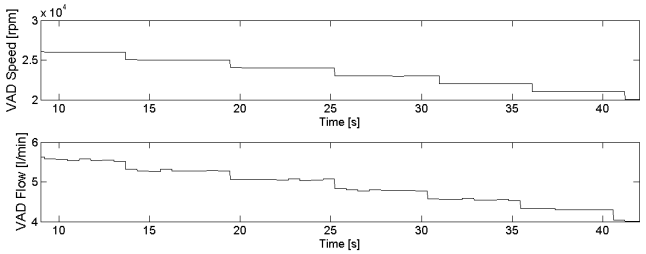

Figure 3. Trend of the speed and corresponding flow changes during the control speed experiments (from 26000 to 20000 rpm).

In this work, the increase of peripheral resistance (i.e. vasoconstriction) has been simulated by gradually changing the silicone tube internal diameter through a clamp from 9.5 mm to 4 mm. The desired flow level has been set at 4.5 l/min during the whole test. As soon as the vasoconstriction is applied, the flow gradually decreases below the desired value. As soon as the ARU detects the flow changes (the mean responsiveness of the ARU is 1 s for starting the PI control), the VAD speed is increased for automatically restoring the desired flow level. The trend of the VAD speed and corresponding flow are shown in Fig. 4 after the application of the vasoconstriction event. The vasoconstriction has been applied for 60 s and then removed, thus reestablishing the original tube diameter. The effect of the vasoconstriction end is a sudden flow increase that is detected by the ARU with a consequent decrease of the VAD speed for restoring the initial conditions of the system (flow = 4.5 l/min and speed = 23600 rpm).

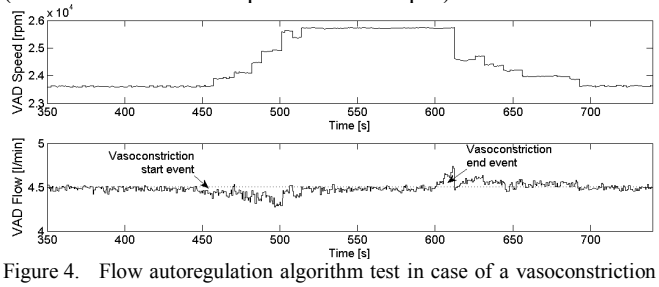

Figure 4. Flow autoregulation algorithm test in case of a vasoconstriction event. The start and the end of the vasoconstriction event are indicated.

C. *Autoregulation algorithms in case of suction events*

The ARU has been conceived in order to autonomously detects suction events that compromise the functioning of an implanted VAD. Suction event usually happens when the inflow tube collapses due to a excessive decrease of the inflow pressure with respect to the atmospheric pressure. In traditional VAD system, this can induce a critic condition for the patient who must undergo medical treatments. Suction can be detected by a sensorized system and can be solved by a stop&go of the VAD. The suction event can be simulated by manually squeezing the silicone tube at the pump inflow. The ARU detects the inflow pressure variations and activates the suction detection algorithm, thus resulting in a VAD reset and reactivation after 30 s (eventually at lower speed), as shown in Fig. 5. This time is compatible with clinical requirements being the natural heart partially active.

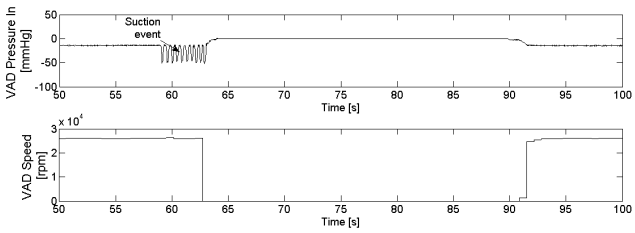

Figure 5. Trend of the VAD input pressure and speed in case of a suction.

IV. CONCLUSION

In conclusion, the ARU device for autoregulation and control for left ventricular assist devices has been tested in an on bench platform with an embedded sensorized pump. The possibility to change LVAD settings both through a local controller and via wireless has been successfully demonstrated. In addition, the autoregulation algorithm have been demonstrated for the continuous regulation of the flow and the automatic detection of suction events. The approach proposed in this paper including a dedicated ARU for the autonomous control of a sensorized VAD will contribute to a deep revolution towards new therapeutic technology-based solutions in cardiology. In this sense, it will be interesting to explore the possibility of implementing autoregulation algorithms to more complex systems, such as total artificial hearts.

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