Simulation of an Electro-Mechanical Resuscitation Device for Cardiopulmonary Resuscitation

Alejandro Mendoza García [1], Stefan Eichhorn [2], Marcin Polski[2], Alois Knoll[1]

[1]Fakultät für Informatik, Robotics and Embedded Systems, Technische Universität München, Munich, Germany
[2]German Heart Center Munich, Clinic for Cardiovascular Surgery, Technische Universität München, Munich, Germany

Abstract

Application of cardiopulmonary resuscitation to people suffering from cardiac arrest has become an effective way of increasing chances of survival. Current CPR is done manually, however new electro-mechanical resuscitation devices are capable of providing chest compressions at a constant rate and depth, even when the patient is being transported.

These new devices give the possibility to generate different compression waveforms additional from the sinus shape given under manual compressions and at different rates. For the exploration of this aspect a simulation system is presented, based on a mathematical model and a simulation engine. This system is capable of generating different scenarios simultaneously.

Several waveforms were introduced into the model and the cardiac output of each shape is presented. Results show that a trapezoidal waveform gave better performance in terms of cardiac output.

1. Introduction

The application of cardiopulmonary resuscitation (CPR) to people suffering of cardiac arrest has become an effective way of increasing chances of survival. Current CPR is carried out manually with a compression depth of at least 5 cm and a rate of 100 compressions per minute (CPM) [1]. This however requires significant amount of force, producing fatigue when applied manually, reducing the effectiveness of the procedure. Additional challenges include the transportation of the patient where compressions cannot be maintained.

New electro-mechanical resuscitation devices (ERD) may solve this problem by providing constant compressions at a specific rate and depth. They are fixed to a baseplate where the patient lies and can be easily transported while continuing CPR.

Additionally the use of ERD bring the possibility of generating compressions different to the regular sinus shape. Previous research has covered this topic analysing the effect of a trapezoid waveform in a porcine model [2]. The presented work focuses on the creation of a simulation system that can help to analyse the effect of different compression curves and at different rates.

The simulation system is presented first with the description of the mathematical model. This consists of a cardiovascular system together with an electro-mechanical CPR device. Afterwards details are given of how the simulation system was implemented which allows simultaneous execution of multiple models. This is followed by the results of simulating different compression curves and discussion.

2. Mathematical model

The model of the ERD was constructed by decomposing the system into a DC electric motor and its mechanical components with the following formulas:

$$\frac{d}{dt}i = -\frac{R}{L}i - \frac{k_v}{L}\omega + \frac{V}{L} \qquad (1)$$

$$\frac{d}{dt}\omega = \frac{k_T}{J}i - \frac{B}{J}\omega - \frac{T}{J} \qquad (2)$$

Where i represents the current, R is the resistance, k_v is the back emf, ω is the rotational velocity, V is the voltage and L is the inductance. In equation 2 k_T is a torque constant, B is the damping coefficient, T is the torque and J is the inertia.

The torque is converted to force given the gear radius in the DC motor with the formula $T = F \cdot r$.

The model of the body was representing using as a reference the work presented in Babbs [3] together with previous models used in our research group [4].

The motion of the sternum in response to the force $F(t)$ is given with the following equation:

$$F(t) - kx_1 - \mu\dot{x}_1 = 0 \qquad (3)$$

Where the sternal displacement and velocity are

ISSN 2325-8861

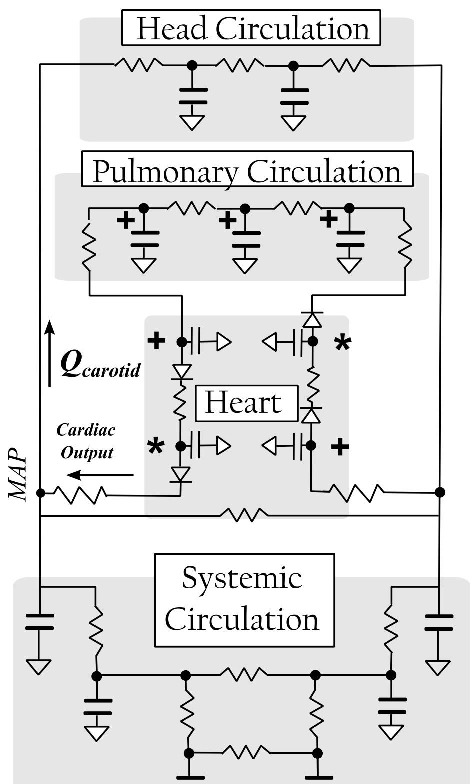

Figure 1. Cardiovascular system configuration.

represented as x_1 and $\dot{x_1}$ **respectively**.

The cardiovascular model was composed using an electric analogy and was divided into head, pulmonary and systemic circulation and the heart composed of four chambers, which is depicted in figure 1. Values of pressure, flow and volume is calculated in each point with the following formulas:

$$P_i = (V_i - V_{i-1}) \bullet 1/C_i \quad (4)$$

$$Q_i = (P_i - P_{i-1})/R_i \quad (5)$$

$$dV_i/dt = Q_{i-1} - Q_i \quad (6)$$

$$dQ_i/dt = (P_{i-1} - P_i) \bullet 1/L\_i \quad (7)$$

In the heart chambers and venous return flow $Q_i = 0$ when $P_i < P_{i+1}$.

The effect of the ERD to the cardiovascular system is produced with the change of pressure in the points marked with **+** and ***** in figure 1 and is calculated with the following:

$$*: \; P_{i*} = P_i + ftp \cdot Epm/do \cdot (x_1 + V_i/A_i) \quad (8)$$

$$+: \; P_{i+} = P_i + Epm/do \cdot (x_1 + V_i/A_i) \quad (9)$$

Where *P* represents the pressure point in the heart chambers, *ftp* is a thoracic pump factor (0.75 for adult) *Epm* is Young´s modulus of elasticity taken as an average of tissue of 12kPa, *do* is a constant representing the front to back dimension of mediastinal soft tissue taken as 10cm, *V* is the current blood volume in the chamber and A is the crossectional area [3].

The parameters of the model such as resistance, compliances and volume distribution were configured based on Babbs specification and on recordings obtained from a porcine animal model where the carotid flow was obtained using a Doppler flow probe while applying 100 CPM with a trapezoidal input waveform and 6 cm depth.

3. Implementation

The mathematical model was developed using a Mathematical Model Language (MML) used by JSim[5] This simulation environment was extended with an engine that allows constant simulation with the introduction of control signals and change of model parameters[6]. The AutoMedic Framework[7] was used to implement generate different compression curves. These curves were sent to individual instances of a simulation model component (SMC) using UDP communication (Figure 2a).

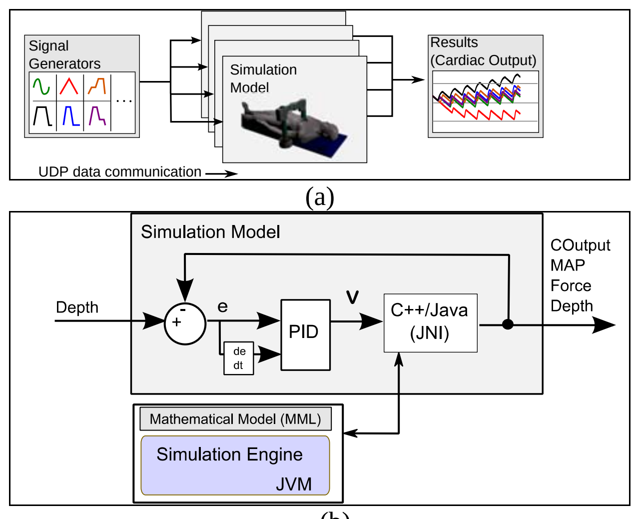

Figure 2. System implementation for multiple simulations (a) and control configuration in a simulation model component (b).

An individual SMC is shown in figure 2b and consists of a PID controller which receives the error difference and derivative between the actual position of the model and the introduced signal. The PID controller obtains the Voltage which is sent to the simulation engine containing the cardiovascular model. Since the simulation engine is programmed in Java and the AutoMedic Framework in

C++ the *JNI* library[8] was used for exchange of data. Each SMC creates an instance of a virtual machines which allows true parallelization of the calculations.

The depth curves are generated at a frequency of 200 Hz, with a simulation step of 0.005 ms. The simulation engine receives this input and generates 5 internal steps for every sample generating data at 1kHz.

After each simulation step model results are sent back to the framework and concentrated to a single graph allowing the direct comparison between the different compression curves.

From this implementation additional curves can be introduced together with the number of SMCs running in parallel.

4. Results

The carotid flow generated by the simulation model, compared to flow extracted from the porcine model is shown in figure 3a. The compression curve of 6cm at 100 CPM is also shown. Resistances and compliances of the systemic circulation and head were adjusted accordingly. Six types of inputs signals were introduced into the mathematical model: A sinus waveform similar to manual chest compressions, a triangular shape with a maximum depth at the middle of the Figure 3.b shows one of these signals (trapezoid signal) where the top curve represents the generated force of the ERD on the chest, the second graph shows the input signal in light gray and the actual plunger position (red) after the PID control effect. The cardiac flow is shown in blue. A cardiac output (CO) of 1.45 L/min and a mean arterial pressure (MAP) of 63 mmHg.

Figure 3.c shows the results of the different curves evaluated in terms of cardiac output at three different compression rates (80 CPM, 100 CPM and 120 CPM). From these results we see a slightly better CO with 100 CPM for most of the curves except the stair down and trapezoid with short compression interval. A CO of 1.35 L/min can be noticed from the sinus wave similar to the manual compressions, and an increase of CO of up to 1.45 L/min when using a trapezoid curve with a compression time of 300 msec.

In terms of implementation, on an Intel core i7 processor at 3.4GHz with 4 cores (multithreaded x2) when simulating 8 models with different waveforms, on a single application with only one virtual machine it needed 5 minutes 7 seconds to generate one second of data at 1kHz, using 14% of the processor capabilities. When multiple instances were generated, each with an individual virtual machine, and communication over UDP one second of simulation was generated in only 29 seconds, using 70% of the processor, making the system 10 times faster than the first case.

Table 1 Processing time for 8 simulation models.

Type	1 sec. simulation	Proc. used
Single process	5 min 7sec	14%
Multiple process (x8+1)	29 sec	70%

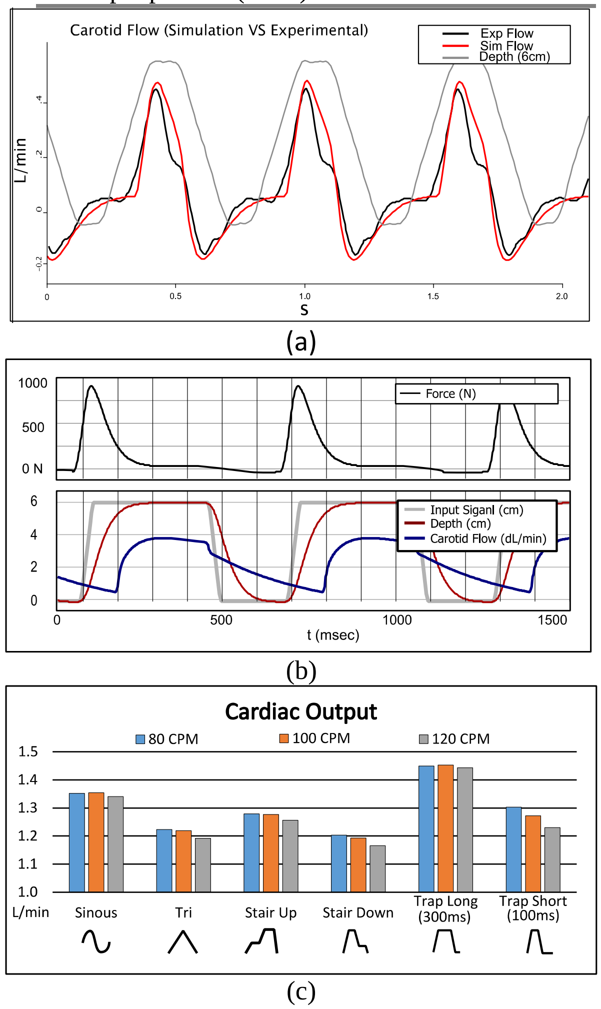

Figure 3 Results: Comparison between experimental model and simulation (a) Simulation outputs (b) Compression types comparison (c)

5. Discussion

Extensive research done by Ong et. al. and Jiang has been done on the comparison between applying manual CPR and using an ERD [9,10]. The results from these studies describe that there is no concrete evidence on showing an advantage of the use of an ERD over manual resuscitation from the perspective of the patient, in some cases even producing negative outcomes. The reason for this may be the use first generation existing ERD devices, however as new devices come into market, improving sensor capability and control, these may be able to adapt to the specific characteristics of the patient, not only facilitating the work of the paramedics, but also improving patient outcome.

The presented results show that by changing the compression curve from sinus to a trapezoidal shape it is possible to improve the cardiac output by 10%, additionally the ERD will be capable of maintaining compression depth and rate, even when the patient is being transported to the hospital.

With the provided simulation system it is possible to do extensive research on different types of curves and control mechanisms that provide best outcome for different types of patients, the following steps will be to modify patient parameters and make the system identify patient characteristics and possible changes of compression resistance that may be produced by the warming up of tissue, and prevent rib rupture due to the use of excessive force.

Acknowledgements

This work has been supported by an unrestricted educational grant from the Bayerische Forschungsstiftung.

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Address for correspondence.

Dr. Alejandro Mendoza García
Lehrstuhl für Informatik VI
Technische Universität München
Boltzmannstraße 3, 85748 Garching
mendozag@in.tum.de