A new method for coronary stenosis detection based on capacitive sensors of a Wireless Sensor Network

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Abstract— **This paper describes preliminary results for coronary stenosis detection. The system implemented is based on a wireless sensor network and is composed of a phantom model of the blood circulation with an appropriate pump and tubes as well as modules used to create the network. At the measurement points there is one Penrose tube with the handmade capacitive sensors attached. A stenosis is created and the output of the electrical circuit is driven to a wireless sensor platform. Data is transmitted in a multihop fashion to the wireless sensor network until they reach the sink attached to a processing unit to be analyzed. This paper describes the evaluation of the method and the implementation of such a system along with some measurements.**

I. INTRODUCTION

An acute myocardial infarction or an acute MI, is a major and common medical emergency. Each year, there are about 1.5 million heart attacks in the United States, leading to more than 500,000 deaths. Most of these deaths—more than 300,000— are sudden, occurring before the patient even reaches the hospital.

The vast majority of heart attacks are a direct result of coronary artery disease. A blood clot or muscular spasm in a narrowed coronary vessel may suddenly block it completely, triggering an infarction in the area of the heart muscle that is normally nourished by that artery [1].

Atherosclerotic disease tends to be localised in the sites of coronary arteries and result in the narrowing of the artery lumen – a stenosis. The stenosis can cause turbulence and reduce flow of blood to the myocardium.

Coronary angiography is considered to be a widespread diagnostic procedure in order to identify the extent and location of disease in the coronary arteries. Two options for interventional or surgical treatment are currently available and widely used: balloon angioplasty and coronary artery bypass surgery.

Restenosis ($\geq$ 50% diameter stenosis) remains the major shortcoming with reported rates varying between 10% and 40%. In recent studies restenosis occurred in 607 patients out of 2690 who underwent percutaneous revascularization and was clinically silent in 335 (55%) [2].

Considering the statistics, it rises the need for reliable continuous monitoring of coronary artery bypass graft or the vessels underwent percutaneous coronary interventional procedures. Coronary angiography is considered to be reliable and provides a snapshot of the coronary arteries condition. The Doppler methods used for detection of stenoses in native arteries can also be used for hemodialysis access grafts and fistulas. Elevated velocities or velocity ratios indicate narrowing of the vessels, with the degree of stenosis related to the increase in velocity [3].

In this paper there is a proposal for a proof of concept method for the identification of stenosis. The scenario that the method is based on is the bypass surgery and the monitoring of the graft for the detection of any narrowing developed at the region of interest.

The system developed for the evaluation of the method is composed of a analogous to the blood circulation hydraulic system. At a point of the hydraulic system a Penrose tube is used and two handmade capacitive sensors are attached to the tube in order to measure the bulging of the tube because of a stenosis.

The output of the signal conditioning circuit is driven to a Tmote sky module [4] where it is sampled and transmitted over a wireless sensor network. The broadcasted signal reaches the sink/gateway via the network in a multihop fashion and the signal is forwarded to the processing unit to be analyzed.

II. METHOD DESCRIPTION

The description of the method is based on a model, which provides a clear view of the variation of pressure and flow inside the circulatory system in the presence of stenosis.

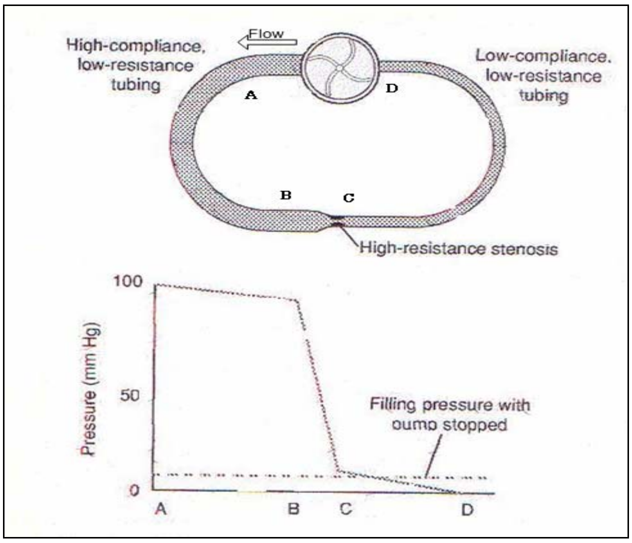

Fig. 1 A model of systemic circulation with stenosis

Liquid is pumped in a high compliance, low resistance tubing. At the C point there is a high resistance stenosis. At the beginning the pump is turned off and liquid is filling the circuit. As soon as the liquid comes to balance inside the tubing, pressure is equal at every point of the tubing (filling pressure).

A volume of liquid will be moved from the high compliance tubing to the low compliance tubing when the pump is turned on. The change of liquid volume at the left side (between A, B points) does not significantly affect the pressure drop because of the high compliance. However, an equal increase at the liquid volume at the right side (between C, D points) causes a significant change in the pressure.
Pressure at the right side is slightly higher than the filling pressure while pressure at the left side is much higher. If the volume moved from the left side is equal to the volume moved to the right side, then the pressure changes reflects the different compliances at the two sides of the circuit [5].

The pressure drop across the circuit is defined at the eq 1.

$$Q = \frac{P_A - P_D}{R} \qquad (1)$$

where Q is the flow , P_A, P_D are the pressure at points A, D respectively and R is the resistance to the flow.

The significant pressure drop and the bulging of the tubing just before the stenosis are detectable if a capacitive sensor is placed near the stenosis.

The bulging can cause change of the capacitance of the sensor by applying force, which moves the capacitance plates and changes the distance between them. A simplified model of a capacitance change due to moving plates is described in eq.2

$$C = \frac{k\varepsilon_o A}{d + x} \qquad (2)$$

where k is dielectric constant of the material between the plates, ε_0 is the permittivity of free space, A is the area of each plane electrode, d is the separation between the electrodes and x is the extra separation caused by the bulging.

The pressure drop across a stenosis is described by the Bernoulli equation (3) for steady flow.

$$P + \frac{1}{2}\rho v^2 + \rho g z = const \qquad (3)$$

where P is the pressure, $\frac{1}{2}\rho v^2$ is the term of kinetic energy and $\rho g z$ is the term of dynamic energy.

Applying the eq. 3 at the model described above

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \qquad (4)$$

which means that because of pressure drop across the stenosis, there is an increase in liquid velocity after the stenosis.

$$\Delta P = P_1 - P_2 = \frac{1}{2}\rho v_1^2 \left[\left(\frac{A_1}{A_2} \right)^2 - 1 \right] \qquad (5)$$

where A_1, the cross section of the tube before the stenosis ,
A_2 the cross section of the tube after the stenosis.
For steady flow profile the pressure drop across a stenosis becomes higher as the stenosis increases which actually decreases the cross section area of the tube.

The application of this observation at a bypass surgery scenario with a venous graft placed can provide much greater bulging in case of restenosis at the graft because of the higher compliance and the elasticity of the venous.

III. EXPERIMENTAL SETUP

The experimental setup is based on a hydraulic circuit which simulates the systemic circulation of blood. The region of interest, in which a stenosis will be created, is a Penrose tube 30 cm long. The elasticity and the compliance of this tube have similar properties to the elasticity and compliance of a venous graft.

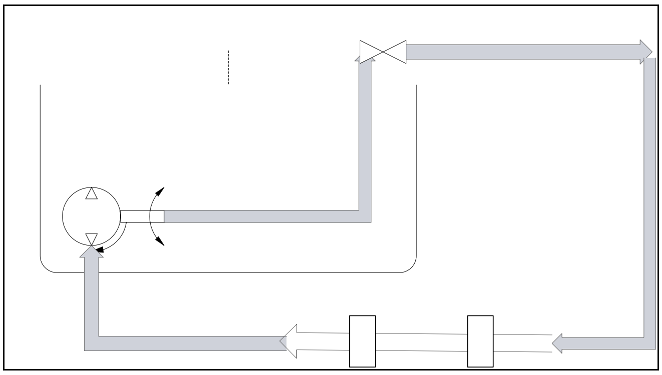

Fig. 2 Hydraulic circuit analogous to the blood circulation

The two capacitive sensors are attached to the tube in a way to cuff the tube.

The tube is pressed flush against the sensor surface until appropriate flattening is achieved. According to the Laplace's Law pressure gradient across a thin-walled vessel is given by

$$P_{in} - P_{out} = \frac{T}{r} \quad (6)$$

Where P_{out} and P_{in} are the pressures outside and inside the vessel respectively, T is the vessel wall tension and r is the vessel radius. If $r \rightarrow \infty$ the measured pressure will be equal to the intra-luminal pressure ($\Delta P \rightarrow 0$) [6].

IV. SIMULATION RESULTS

The capacitive sensors used for the experimentation are handmade and created by copper using a soft material as dielectric. After measurements of the capacitance of the sensors, it has been concluded that the dielectric constant of the material used is between 1.2 and 1.6.

The area of the plates is approximately $1600\,mm^2$ which gives a capacitance value of approximately 4pF. A realistic estimation of the capacitance value is from 2.8pF for plate distance equal to 0.7cm to 19.8pF for plate distance equal to 0.1cm.

The capacitive sensor is connected to an AC bridge via wires that act as stray capacitances. The balance of the bridge is dependent on the stray capacitances, the value of the handmade capacitance and the capacitance at the other branch of the bridge.

The output of the AC Bridge is routed to an instrumentation amplifier made of TL081 that amplifies the signal approximately 90 times.

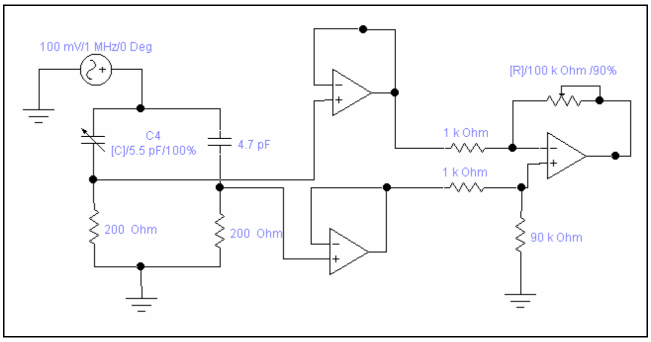

Fig 3 Simulation circuit of AC Bridge and instrumentation amplifier

The parametric simulation is based on a successive 5% decrease of the capacitance value due to the increase of the distance of the plates and at each step there is a simulation of the output of the circuit. The capacitance values are calculated using the eq. 2 for a given k and plate area.

The table 1 below depicts the simulation results taken based on the assumption that the voltage of the right branch of the AC Bridge remains constant and the capacitance is equal to 4.7pF.

Simulation results reveal that the circuit output is very much dependent on the initial value of the handmade capacitance. This is due to the fact that at the right branch of the bridge there is a constant value capacitance. This could be solved using a variable capacitance in the range of a few pF even if it is very hard to find and adjust such a capacitance.

Table 1 Simulated Voltage Output as a function of capacitance changes (plate distance)

Capacitance (pF)	Distance between Plates(cm)	Output (mV)
4,96375	0,4	15,39
4,7155625	0,43	10,93
4,479784375	0,45	6,48
4,255795156	0,48	2,03
4,043005398	0,5	2,43
3,840855129	0,53	6,88
3,648812372	0,55	11,34
3,466371753	0,58	15,8
3,293053166	0,6	20,25
3,128400508	0,64	24,7
2,971980482	0,67	29,17
2,823381458	0,7	33,62

The output of the bridge based on the values of the handmade capacitance is shown in figure 4.

The output is not monotonic and has a point corner at which the bridge is balanced. If the handmade capacitance has such a capacitance value that the bridge output is at the left side of the corner then further bulging will reduce the output signal and after a point there will be an increase (this is the case of capacitive sensor B). If the handmade capacitive sensor has a value so that the bridge output is at the right side of the corner then the stenosis will further increase the distance between plates and the output of the bridge will be monotonically increasing.

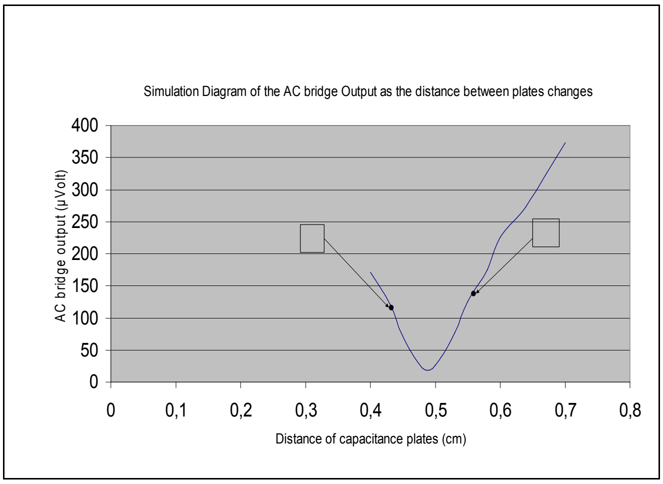

Fig. 4 Simulated AC Bridge output as a function of distance between plates

V. MEASUREMENT RESULTS

A stenosis model was developed in order to calibrate the system and define a unique relation between the output of the circuit and the percentage of stenosis [7]. The decrease of the vessel diameter and subsequently the decrease of the cross section area of the vessel can be simplified by the eq 7.

$$\frac{4\pi\left(\frac{d}{2}\right)^2 - 4\pi\left(\frac{d-x}{2}\right)^2}{4\pi\left(\frac{d}{2}\right)^2} = \frac{2dx - x^2}{d^2} \qquad (7)$$

A stenosis created by applying pressure at the outside walls of the Penrose tube. The applied pressure causes a constriction of the tube and the constricted diameter is measured with a thickness gauge.
Assuming that the constriction is equal from all sides of the tube wall, the estimated percentage of stenosis is summarized in table 2.

Table 2 Stenosis calculation based on model of stenosis and measurements of the thickness of the tube

Thickness Gauge d-x (mm)	x (mm)	Stenosis (%)
6	1	23
5	2	44
4	3	61
3	4	75
2	5	86
1	6	94

The reference point of the measurements is set to the value measured at each sensor without flow or stenosis. Sensors are placed at the beginning and at the end of the tube as it is shown at figure 5.

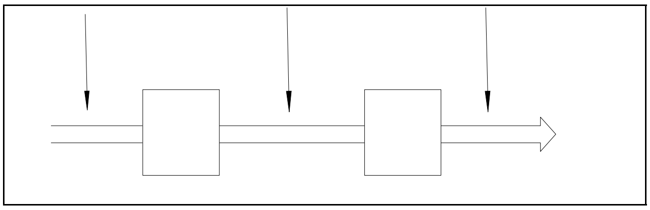

Fig. 5 Measurement Points across the Penrose tube

Each sensor repeatedly conducts sets of measurements for various stenoses caused at every point. Data acquisition is achieved by means of direct capturing from the oscilloscope and transfer to the processing unit via GPIB interface or by routing the signal to the ADC of a mote which samples the signal and transmit it to the wireless sensor network.

The main purpose of the network is to relay signals to the processing unit. The key feature of this layer is the redundancy and the functionality.

Motes interfacing with sensors are part of the network collecting data for the network. The routing is flexible and it establishes automatically a communication link between a new member node, and the sink. Malfunctioning can cause topological changes and the reorganization of the network is required. Redundancy is achieved by multihop communication (Fig. 6). In the case of failure of one node its functionality is overtaken by other nodes within the range of Wireless Sensor Network (WSN) [8].

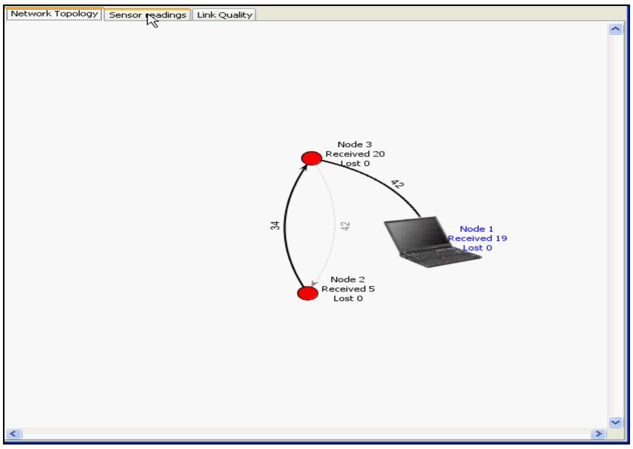

Fig. 6 Multihop communication

Data routed to the sink are imported to the processing unit (laptop) via the sink. The sink is a Tmote sky module attached to the laptop which receives packets coming from the network and forwards them via USB interface provided by the mote.

The signal at the processing unit is a sinusoidal which has been amplified by the instrumentation amplifier and the useful information is carried at the amplitude. The change of the capacitance causes changes at the AC Bridge output and at the second level of the instrumentation amplifier the subtraction of the signals of the two branches of the Bridge is amplified.

For every set of measurement there a calculation of the RMS value, which significantly changes while the bulging increases.

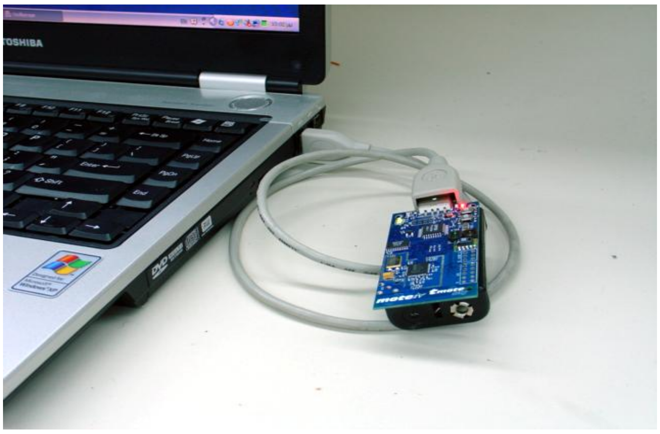

Fig. 7 Wireless sensor module sink

Data processed and analyzed are presented at the following table 3.

These two particular points 2A, 3B symbols the point of measurement and the capacitive sensor that measured the various stenoses. These are the points of great interest because the bulging of the tube at A, B sensors respectively is the maximum as the constriction of the tube is increased.

Table 3 Measured RMS values as a function of tube diameter

Sensor location	Tube diameter measured with thickness gauge (mm)	RMS value calculated (Volt)	RMS value minus RMS no flow value (Volt)
2A	5	0,0083	0,001
	4	0,0083	0,001
	3	0,0087	0,0014
	2	0,0088	0,0015
	1	0,0096	0,0023
3B	5	0,0089	0,0006
	4	0,0082	-1E-04
	3	0,0085	0,0002
	2	0,0091	0,0008
	1	0,0093	0,001

The measurements taken at these points are shown at the figure 8 below.

The correspondence of stenosis percentage and tube diameter measured with the thickness gauge is diverted from the model described above and is depicted in the next table. Lower values for the stenosis percentage are not easily detectable as the bulging of the tube is not significant and the distance of the plates of the capacitive sensor remains approximately the same.

Table 4 Tube diameter and Stenosis Percentage

Tube diameter measured with thickness gauge (mm)	Estimated Stenosis Percentage (%)
5	44
4	61
3	75
2	86
1	94

The first set of measurements was made for diameter of tube equal to 5mm for the capacitive sensor A. It provides after the processing with a value of 0,0083volt (before the subtraction of the RMS value of no flow measurements at point 2). The next value is approximately equal to the previous and there is a monotonic increasing RMS value as the bulging increases or as the stenosis increases.

The combination of this initial value with the simulated curves and the value closer to the measured one provides the approximate capacitance of sensor A which is 3,65pF and this capacitance is placed right from the corner of figure 4. This is implied by the output of the circuit for the capacitive sensor A.

For the capacitive sensor B, the value measured at a diameter of 5mm is 0,0089volt (without subtracting the RMS no flow value at point 3).Given that the next measured RMS value is lower than the first measurement, it is understood that capacitive sensor B is placed left from the corner of figure 4.The closest simulated point to the measured one is 0,01 volt at which the capacitance is equal to 4,7pF.

Figure 8 depicts a monotonic trend for stenoses greater than 60%. The different values of the two curves are mainly because of the different value of the two capacitive sensors.

Stenosis at measurement point 2 cause bulging at the portion of tube before the stenosis but it has been observed that after the stenosis the flow becomes turbulent and this affects the measurements of capacitive sensor B.

The way the two capacitive sensors were placed like a cuff is considered to be a stenosis which is in series with the various stenoses examined and this may affect measurements and resolution of the system.

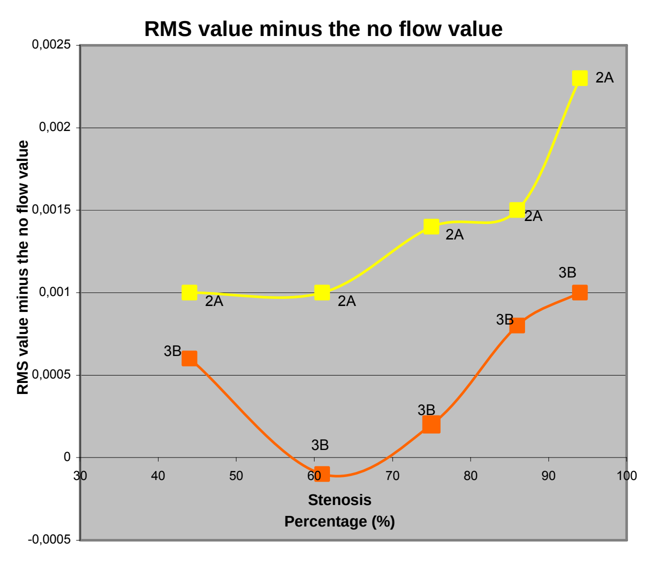

Fig 8 RMS values minus the No flow RMS value

VI. CONCLUSIONS –FUTURE WORK

In this paper there is a proposal for a method of identification and measurement of stenosis. The system implemented is based on wireless sensor network which interfaces with the circuit of the sensors and relays data to the processing unit in a multihop fashion.

A wireless sensor network interfacing with different kind of sensors like accelerometers, capacitive sensors for stenosis detection, electrodes for ECG acquisition, implements data integration and evaluation of information for accurate event detection of biomedical interest. Routing and energy consumption are open issues for a body sensor network that handles information from vital signs.

The theoretic background of the method is focused on the fact that a stenosis has a significant resistance and across the stenosis there is a pressure drop and a bulging of the elastic tube just before the stenosis.

The method can be verified by using another sensor technology like pressure sensors to measure the pressure drop, or any other kind of sensing devices in order to acquire a signal of a stenosis presence in a portion of vessel.

This paper is based on a scenario of bypass surgery and restenosis that may occur in many patients. Implantable sensors capable of identifying and measuring a stenosis inside the body in cooperation with sensors placed outside the body to measure certain physiological parameters, can implement a wireless sensor network known as body sensor network in order to monitor the health status of a subject. Sensors implanted will be pre sutured as part of the bypass operation and pre calibrated.

Power supply solution is under consideration and the design is based on two parts. The first part receives the transmitted radio frequency (energy) and extracts the necessary constant voltage. The second part transmits the measured values back to the base unit.

Certain clarifications have to be taken into account in the future for this method. It has not been clarified yet the interference of the change of flow profile to the measured signals. Another issue that needs to be studied is the stray capacitances and how the signal and the capacitive sensors do not affect each other.

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