An application of pressure estimation in minimally invasive surgery

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An Application of Pressure Estimation in Minimally Invasive Surgery

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Abstract - ***Because of its many advantages, the minimally invasive surgery (MIS) becomes more and more important as a medical technique. During MIS, the operation area has to be flushed with a rinsing fluid for a suitable expansion and to maintain visibility. This is done with the help of a special medical device called double roller pump (DRP). By controlling the pump's speed for the inflow and outflow of fluid, the pressure in the area is changed respectively. It is possible to design a controller for a stable pressure by using directly measured pressure in the surgical area. However, in case of a real operation, the pressure in the part of body cannot be measured directly because of the safety of the patient. Therefore, this paper presents a solution to reconstruct the pressure in the operation area by using the available sensor data at the double roller pump for the application of a knee arthroscopy, as an example of MIS. A Luenberger observer and a Kalman filter were implemented on simulation as well as on a real-life simulator. The estimated results illustrate that the Kalman filter works better than the Luenberger in terms of fast-tracking and noise cancelling.***

Keywords: ***Minimally invasive surgery; double roller pump; arthroscopy; pressure estimation; observer***

I. INTRODUCTION

Minimally invasive surgery (MIS) is an advanced surgical method for the minimization of incisions on the patient body. The MIS supports the reduction of trauma problems, postoperative pain, blood depletion, and time of recovery. This method uses specialized instruments and medical therapy device for the visibility, clinical diagnosis, and tissue repairs in the operation area. These special instruments consist of trocars with flexible fiber optical system, tiny surgical instruments as well as plastic pipes. For a clear image during MIS, rinsing fluid is used for flowing through the surgical area via the plastic pipes. A suitable pressure for the expansion is maintained by the flows of fluid in the closed area. The flows in and out to the surgical area are controlled by using the medical device. Fig. 1 is an example of MIS in case of the knee arthroscopy utilizing a double roller pump (DRP) as a medical therapy device [1, 2]. This device has been implemented for pressure control in the operation area. Medical device control technique is also a crucial element to the quality improvement of MIS.

Many types of the medical devices have been used with different control algorithms during the technical development in MIS. These devices control the pressure in the operation area via the flows of flushing fluid. Firstly, a gravity method was used with a fluid bag for a suitable pressure via the inflow of fluid to the area. That was a simple method for the benefits of low cost and ease of use. The pressure was controlled by the height of the fluid bag and the opening of the valve. Secondly, a single roller pump has been used since the 1970s [3]. With this method, the pressure in the operation area depends on the inflow of fluid by the pump's speed. Furthermore, a double roller pump has been applied to control the pressure by the inflow and the outflow [3, 4]. In some applications, the inflow and the outflow were controlled independently of each other. In addition, the research from reference [1] was proposed to offer a solution of pressure control effectively and automatically. In this solution, the feedback signals for controller design was measured directly from the operation area. But these measured data are not acceptable in the real-life operation because of the risks for the patient. To deal with this problem, an application of pressure estimation in the knee arthroscopy is offered in this contribution. The estimation is used to replace the measurement in the operation area. Observer design was implemented for this purpose. Luenberger observer and the Kalman filter methods were applied in simulation as well as in the real-device simulator. These state estimators are essential to provide feedback to the controller instead of measured data in the knee during MIS.

Section II describes the modelling of the system. Section III presents the methods of estimation. Section IV shows some results and discussion. And the conclusion is in Section V.

II. DESCRIPTION AND MODELLING OF THE SYSTEM

As shown in Fig. 1, a DRP is used together with the plastic pipes for the knee arthroscopy in MIS. The pressure in the knee area will be changed significantly when the inflow of fluid is different from the outflow. The DRP includes the two DC motors and the roller wheels. The pressures at the DRP are created by the speeds of the motors. These pressures are measured from the available pressure sensors. The pressure at each roller pump causes the flow of fluid in the pipe. Therefore, by controlling the motor speeds for the two directions of flow, the pressure in the surgical area is controlled respectively.

Depending on the revolution n_i of a DC motor, the fluid flow Q_{pi} at each pump is determined by (1). Noting that the motor *M1* is represented to the direction of the inflow at the roller pump1 (called Q_{p1}). Similarly, the motor *M2* is represented to the direction of the outflow at the roller pump2 (called Q_{p2}).

$$Q_{pi} = f(n_i). \quad (1)$$

Where: n_i is the revolution of the motor number i ($i = 1,2$), and Q_{pi} is the flow of fluid at the pump number i.

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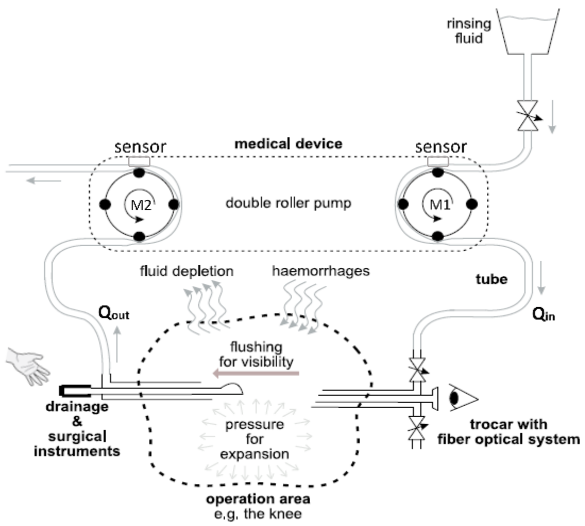

Figure 1: *An overview of the system operation in the knee arthroscopy*

The changes of pressures from the pumps through the pipes ($\dot{p}_{p1}$ *and* $\dot{p}_{p2}$) are defined by (2) and (3), whereas C_{pipe} is the hydraulic capacity of the pipe. Q_{in} is the inflow from the pipe to the operation area. And Q_{out} is the outflow from the operation area to the other pipe. Q_{p1} and Q_{p2} are the flows at the pump1 and pump2 respectively.

$$\dot{p}_{p1} = \frac{Q_{p1} - Q_{in}}{C_{pipe}} . \quad (2)$$

$$\dot{p}_{p2} = \frac{Q_{p2} - Q_{out}}{C_{pipe}} . \quad (3)$$

From the two directions of fluid flows, the sum of flows called *'Q'* in the operation area is calculated by (4).

$$Q(t) = Q_{in} - Q_{out} . \quad (4)$$

The pressure is dropped by the resistance of the pipe. Therefore the differences between the pressures at the DRP (p_1 and p_2) and the pressure in the knee p_{knee} are described by (5) and (6).

$$p_1(t) = p_{knee} + dp_1 = p_{knee} + R(t) \cdot Q_{in} . \quad (5)$$

$$p_2(t) = p_{knee} - dp_2 = p_{knee} - R(t) \cdot Q_{out} . \quad (6)$$

Where: $R(t)$ is the resistance factor of the pipes (the two pipes have the same characteristics). This is a nonlinear factor. The residual of dp_1 is the difference between the pressure at the pump1 and the pressure in the knee. And dp_2 is the difference between the pressure in the knee and the pressure of the pump2.

During the period of investigation, the process of the knee arthroscopy was constructed for test and validation. The real knee thereby was not allowed in the experiments. For the replacement of the real patient knee, a plastic ball with the volume of 1.6 litres was used as a model of the knee in MIS.

For the purpose of eliminating troubles of haemorrhage and fluid depletion, the pressure in the knee p_{knee} needs to be controlled close to the desired value. The reference of pressure in the knee was suggested at the range of 25 – 60 millimeter of mercury (mmHg) over the ambient pressure [3]. This is approximated to the range of 3000 – 8000 in pascal unit (Pa). With the reference pressure, whenever a surgeon makes a drainage action for some change of outflow Q_{out}, then the inflow Q_{in} will be automatically adjusted to keep the pressure p_{knee} stable. From the real condition of unmeasurable pressure p_{knee} in the real patient, the need is to estimate the pressure in the knee for the replacement of the measurement. Section III presents the methods of estimation which were implemented on simulation and also on real-device simulator of the knee arthroscopy.

III. METHODS OF ESTIMATION

State observer design is one of the estimation methods which have been applied in a wide-range of control engineering. Luenberger observer and Kalman filter were implemented in this research. Fig. 2 is a structure of the controlled process including an observer of the pressure in the knee arthroscopy. The control signal u_c is generated depending on the error between the reference and the estimated pressure. The DRP is controlled by u_c signal. The pressures at the two pump (p_1 and p_2) are measured by the pressure sensors. These pressures produce the flows of fluid in the two pipes (one pipe for inflow and the other pipe for the outflow). The pressure in the operation area depends on the difference between the inflow (Q_{in}) and the outflow (Q_{out}). These flows are determined by the lookup tables from the experiments. The main function of the observer block is to estimate the pressure of the knee model for a sensorless in the surgical area. The observer is executed by using the flows information and the measured pressure from the DRP. As shown in Fig. 2, the measurement data at the pump1 (pressure p_1) was chosen for the observer.

As described in section II, a plastic ball was used as the behavior of the knee in experiments. The state of pressure p_{knee} is changed when the sum of flow Q is nonzero. This change is indicated by (7), (8) and (9) in which V_{air} is defined as a variable of air volume inside the operation area.

$$\dot{p}_{knee}(t) = -\frac{p_{knee}(t) \cdot \dot{V}_{air}(t)}{V_{air}(t)} . \quad (7)$$

Where:

$$V_{air}(t) = V_{air0} - \int_0^t Q(t)dt , \quad (8)$$

V_{air0} is a constant, an initial value.

$$\dot{V}_{air}(t) = -Q(t) = -(Q_{in} - Q_{out}). \quad (9)$$

From (7) and (9), it is clear that the state of pressure in the knee model p_{knee} is a nonlinear element which is depended on the change of air volume inside the knee.

By defining the hydraulic capacity of the knee model:

$$C_{ball}(t) = \frac{V_{air}(t)}{p_{knee}(t)} , \quad (10)$$

and substituting (9) to (7), then the state space equation of the knee model becomes:

$$\dot{x} = \dot{p}_{knee} = \frac{1}{C_{ball}(t)} Q_{in}(t) - \frac{1}{C_{ball}(t)} Q_{out}(t). \quad (11)$$

And (5) can be rewritten as a measured output equation:

$$y(t) = p_1(t) = p_{knee}(t) + R(t) \cdot Q_{in}(t) . \quad (12)$$

Equations (11) and (12) are equivalent to the general form in state space:

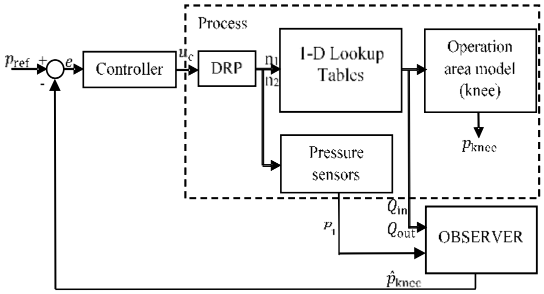

Figure 2. *Observer design in the controlled process of MIS*

$$\dot{x} = A \cdot x + B \cdot u + N \cdot w\,, \quad (13)$$

$$y \quad = C \cdot x + D \cdot u + v\,. \quad (14)$$

Where: Input: $u = Q_{in}$;
Output: $y = p_1$;
State: $x = p_{knee}$;
Disturbance: $w = Q_{out}$; $v = 0$.

And the matrices:

$$A = [0]; \quad (15.a)$$

$$B = \frac{1}{C_{ball}(t)}; \quad (15.b)$$

$$C = [1]; \quad (15.c)$$

$$D = [\ R(t)\ ]; \quad (15.d)$$

$$N = -\frac{1}{C_{ball}(t)}. \quad (15.e)$$

With N is called the noise gain matrix of the process.

From (5) - (12), it can be seen that the process of the knee arthroscopy is a nonlinear model. In experiments and investigation from [1], the process was linearized for the controller design. In this contribution, thereby the observer design in linearized process is mentioned. Therefore, the Luenberger observer and basic Kalman filter were chosen for the implementation.

A. *Luenberger Observer*

This method of observer design is nearly the same as the regulator of the pole placement method.

The characteristic equation of the state space in the knee model:

$$det(s \cdot I - A) = 0 \quad (16)$$

has the only eigenvalue: $\lambda = 0$ (Where: I is a unity matrix).

The Luenberger observer is described in (17) as well as in (18) from the control theory of [5].

$$\dot{\hat{x}} = A \cdot \hat{x} + B \cdot u + L[y - (C \cdot \hat{x} + D \cdot u)]; \quad (17)$$

$$\dot{e} = (A - L \cdot C)e\,. \quad (18)$$

Where: the state error $e = x - \hat{x}$; $\dot{e} = \dot{x} - \dot{\hat{x}}$; and L is the observer gain.

The state estimation matrix is:

$$(A - L \cdot C) = [0] - [L] \cdot [1] = -L\,. \quad (19)$$

The characteristic equation of the observer is:

$$det(s \cdot I - A + L \cdot C) = s + L = 0 \quad (20)$$

The eigenvalue of (20) is: $\lambda^* = -L$.

Or: the observer gain:

$$L = -\lambda^* \quad (21)$$

λ^* is also called the desired pole of the observer, which can be chosen with any of negative pole.

The gain of L is depended on the chosen pole of the observer. The result of the observer is shown in section 4 with the chosen pole: $\lambda^* = -5$.

B. *Kalman Filter Observer*

The basic Kalman filter is used as an optimal observer in linearized process. The main function of the Kalman filter works on two steps of prediction and correction recursively. This is to minimize the error of the estimated state $\hat{p}_{knee}$ comparing to the measured data of p_1 of the DRP. Equation (17) can be rewritten as (22) for the Kalman filter observer [6], whereas K is called the Kalman gain.

$$\dot{\hat{x}} = A \cdot \hat{x} + B \cdot u + K(y - \hat{y}). \quad (22)$$

Where: the measured output y is described in (12), and the estimated output $\hat{y}$ is calculated by (23).

$$\hat{y} = C \cdot \hat{x} + D \cdot u \quad (23)$$

Assume that there are two noise signals: the process noise $\{w\}$ and the measurement noise $\{v\}$ as in (13) and (14). The zero-mean uncorrelated Gaussian random process $\{w\}$ has the covariance W at the time t. Similarly, $\{v\}$ has the covariance V at the time t. At the first step of state prediction, the state of the knee pressure $\hat{p}_{knee}$ is calculated based on the corrected state $\hat{p}_{knee}$ from the previous cycle. In addition, the prior predicted error covariance P^- is also calculated as well. This step is presented by (24) and (25). At the second step of state correction, the error of the estimating state is obtained based on the predicted state comparing to the measured output. And the corrected state is updated from the predicted state and the residual error by using the current value of the Kalman gain K. The Kalman gain is calculated by (26), and then the error covariance P^+ is updated by (27).

$$\dot{\hat{p}}_{knee} = A \cdot \hat{p}_{knee} + B \cdot Q_{in} + N \cdot Q_{out}$$
$$+K[p_1 - (C \cdot \hat{p}_{knee} + D \cdot Q_{in})]. \quad (24)$$

$$\dot{P}^- = A \cdot P + P \cdot A^T + N \cdot W \cdot N^T$$
$$-P \cdot C^T \cdot V^{-1} \cdot C \cdot P. \quad (25)$$

$$K = P \cdot C^T \cdot V^{-1} = P \cdot V^{-1}. \quad (26)$$

$$\dot{P}^+ = N \cdot W \cdot N^T - K \cdot V \cdot K^T. \quad (27)$$

Table 1 shows the parameters used in the simulation as well as in the observer of the knee arthroscopy, where p_0 and V_{air0} are the initial conditions of the pressure and the air volume in the knee model respectively. The parameter of C_{pipe} is the hydraulic capacities of the pipe.

TABLE 1. PARAMETERS USING IN MODELLING PROCESS AND IN OBSERVERS

Parameters in the knee arthroscopy model		
Parameter name	***Value***	***Unit***
Ambient pressure: p_0	101325	Pa
Initial air volume in the ball: V_{air0}	0.0006	liter
Hydraulic capacity of the pipes: C_{pipe}	$9.75e^{-11}$	m^3 / Pa

IV. RESULTS AND DISCUSSION

Fig. 3 shows the results of Luenberger observer and Kalman filter method. It can be seen that the estimated state from the Kalman filter is more accurate than the state from the Luenberger method. In addition, the Kalman filter observer has a better response in fast-tracking compared to the measured pressure in the knee model.

Fig. 4 is the comparison of the results between the two estimation methods implemented in real-device experiments. It can be seen that some errors between the measured state and the estimated state still exist. This point of view can be explained by the usage of nonlinear factor *R(t)* in (12). This factor was calculated relatively by using the measurements of pressure error *dp1* and the flow Q_{in} in the pipe. Therefore the parameters of *R(t)* might not be exact to the real process. This causes the error in the estimation.

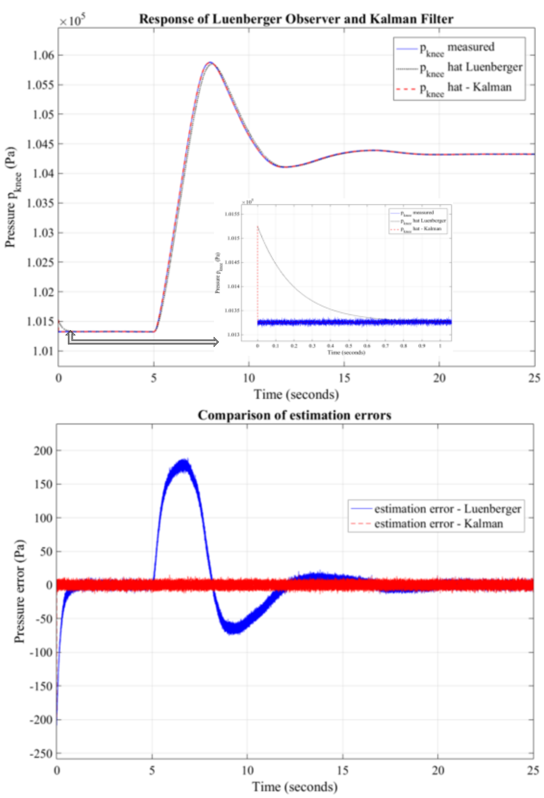

Figure 3. *Comparison of the estimated results in simulation*

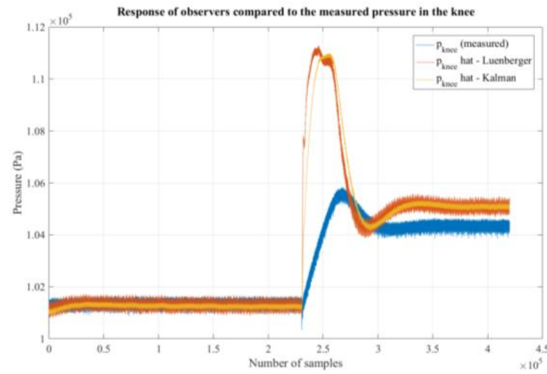

Figure 4. *Comparison of the estimated results in the real-device simulator*

V. CONCLUSION

The paper introduced an application of pressure estimation in the knee arthroscopy. The estimators were designed based on the two methods of Luenberger observer and Kalman filter. These observers were tested in simulation and in real-life device model. The pressure in the knee model was estimated by using measured data from the available pressure sensor of the roller pump1. The estimated results solved the problem of unmeasurable pressure in real-life application of MIS. The results from the two methods were compared in section 4. Although the results illustrate that the Kalman filter is better than the Luenberger observer in terms of fast-tracking and noise eliminating. But in the real-device experiments, these observers need to be modified for more exact in estimation. For the further quality of estimation in the nonlinear process, the basic Kalman filter can be improved by utilizing the extended Kalman filter (EKF) [6]. For further research, the pressure in the operation area can be estimated by using the available data from the pressure sensor at the roller pump2, or event using both the two sensors data. The smoother estimated state should be better for the controller without using the measured data. The improvements of the estimating methods will bring more efficiency in the application of pressure estimation in minimally invasive surgery.

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