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Optimizing robotic actuator, trajectory tracking and fuzzy control

PhD Thesis

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1 Introduction

There are many attempts trying to define what the word 'robot' means. Most of these definitions describe some kind of autonomous or computer controlled machine with a capability to perform some specific tasks.

However, the first appearance was introduced into the public consciousness with Karel Čapek's drama, R.U.R. (Rossum's Universal Robots) in the year 1921, where the Czech word 'robota' was referred to a synthetic humanoid instead of an electromechanical device [13].

To have a deeper perspective in the different designs, robotic devices should be first categorized into smaller groups. There are different types of classifications. For example, the degrees of freedom or the implemented level of intelligence [14] or the classification by application or by the way of motion [15]. Industrial, domestic/household or military robots are examples for the latter, while wheeled, legged, flying or stationary robots are categorized by the types of locomotion and kinematics. A newly emerged field is the so-called collaborative robotics, where the human safety approach implemented originally in the domestic/household robots are introduced to the operation of the industrial manipulators.

Therefore, basic researches aim towards the application of pneumatic artificial muscles (PAMs) since their inherent elasticity makes these relatively new type of actuators optimal for the development of either collaborative or legged robots. The different aspects of PAM technology and the new results achieved in this study are discussed in details in Thesis 1. Another important aspect in the field of robotics is the precise trajectory tracking which is equally important for mobile and legged robots. My new developments on this field can be found in Thesis 2. Finally, application of a fuzzy control system might be a good choice to develop an efficient robotic device or to operate the actuators effectively and it could be also useful for higher controlling levels. The details about my results regarding the fuzzy systems are discussed in Thesis 3.

2 Optimizing the transfer function and designing a new force to torque transmission system for pneumatic artifical muscle (PAM) actuator

In the last decade, automation processes have been gaining more and more attention as the available actuators are getting cheaper and stronger. While efficiency in robotic manipulator technology has been constantly evolving, a new criteria has recently emerged, namely human safety.

Pneumatic artificial muscle (PAM) is a relatively new type of unconventional actuator which can be built into robotic joints. There are many advantages of using PAM actuators instead of a conventional one. Mostly, the extreme power-to-weight or power-to-size parameter is the main factor in practical applications. Furthermore, PAM actuators can be also utilizable in robotic joints, since PAMs are inherently elastics, therefore the manufactured joint will also be flexible.

Although the PAMs are very simple thus cheap constructions, controlling them is a difficult problem due to the highly nonlinear characteristics of the generated force. The main problem is that the maximum force produced by a PAM at a fixed pressure is the nonlinear function of the contraction. Basically, near 0 % contraction, also known as the relaxed state, the PAM can produce tremendous force, while this will decrease drastically and nonlinearly near the maximum contraction.

The accurate modeling of the actuator is necessary to develop a reliable and precise system when using a PAM component. Therefore an exponential function was first selected as a core function to describe the static correlation between the force (y), contraction (κ) and the required pressure (p). The exponential function provides the best approximation for the highly dynamic change of the measured data points instead of using trigonometrical or low ordered polynomial. The exponential function in equation (1) uses only four unknown parameters and it can express the correlation between contraction and force for a fixed pressure.

$$F_{core}(\kappa) = a \exp^{\left(\frac{1}{\kappa+b}\right)} + c\kappa + d \quad (1)$$

Where (a,b,c,d) are unknown parameters.

The next step is to make some parameters of the core function pressure dependent resulting in a general function called transfer function. The general form of the core function in equation (2) is using only six unknown parameters.

$$F_y(p,\kappa) = (ap+b)\exp^{\left(\frac{1}{\kappa+c}\right)} + (d\kappa+e)\,p + f \tag{2}$$

Where (a,b,c,d,e,f) are unknown parameters.

From equation (2) the variable p can be expressed by equation (3) as an inverse function, which can be used in an open looped control [8].

$$F_p(\kappa,y) = -\frac{b\exp^{\left(\frac{1}{\kappa+c}\right)} + f - y}{a\exp^{\left(\frac{1}{\kappa+c}\right)} + d\kappa + e} \tag{3}$$

Where (a,b,c,d,e,f) are the same parameters from equation (2).

The transfer function published in 2009 first was used for comparison, see reference [6] for more details. As a result, the presented function gave approximately 7.1 % smaller RMSE value for the whole useful operating range, as seen in Fig. (1).

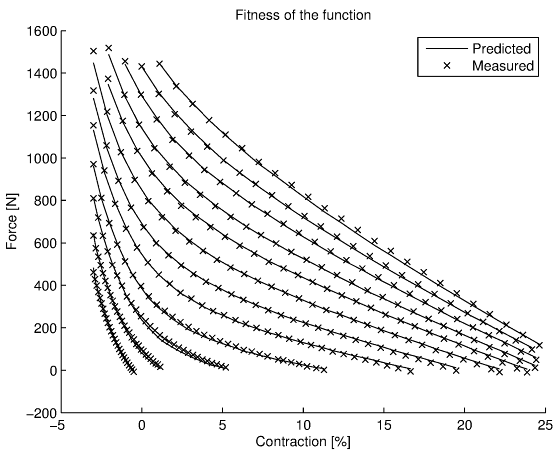

Figure 1: Comparison of measured and predicted data

The compactness of the newly introduced transfer function allows that, only nine measurements are necessary to refit the model upon recalibration instead using the total of 340. This function is also more precise at the extreme working range when the calibration measurements are carefully selected.

Another main advantage using PAMs as actuators is that these can be built into robotic joints without applying heavy and complex gearing mechanisms such as epicyclic drive [16] or harmonic drive [17]. However, the nonlinear characteristics of PAMs make these actuators difficult to use in these applications as well. The T_{useful} torque is less than one third and can barely reach higher than half of the theoretical maximum at its peak, when a regular circular shaped transmission unit is applied. The basic idea was to construct a spiral and cable transmission unit with a non-circular cable spool in order to achieve better force to torque converting capability.

A framework was developed, which supports various ways of defining the disk geometry, which are not limited by closed form functions as seen in reference [18], but can also be expressed numerically. The non-circular shaped geometry should also be optimized by certain profile or criteria to enhance the effectiveness of the transmission. To enhance the utilization of the torque generated by PAMs, a specific non-circular disk geometry was optimized with the framework. An experimental device was also constructed to validate the simulations, which allow to test different disk shapes, and measure the correlation between the contraction of the simulated PAM and the rotation of the central disk.

The testing of the framework was carried out through a virtual upgrade of a regular disk and a non-circular shaped transmission system as well with torque amplification in mind. For the latter, the r_s radius was given as a third order polynomial function of the θ angle with the following equation.

$$r_s(\theta) = f_1\theta^3 + f_2\theta^2 + f_3\theta + f_4 \tag{4}$$

Where the missing f_i coefficients were find with genetic algorithm.

The simulation result showed a significant improvement on the whole torque range as seen in Fig. (2).

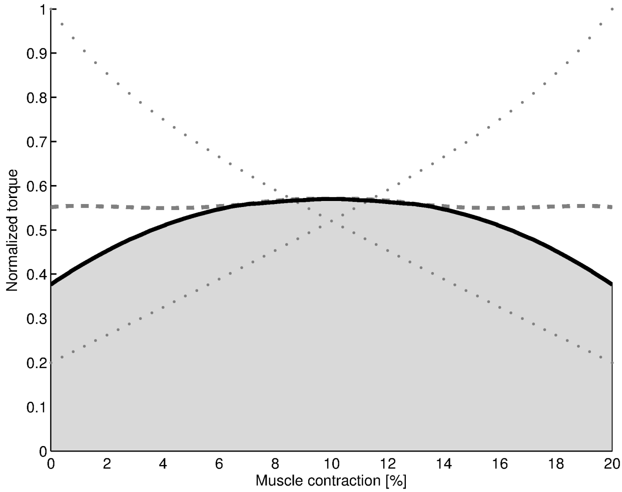

Figure 2: The normalized torque values (dashed line) in an antagonistic setup of PAM actuators using the optimized non-circular shaped disk element as a gear system. T_{useful} torque range is shown by the grey area as a function of muscle contraction at the maximum operating pressure, while the Y axis is normalized to the reference design torques (dotted line) in order to make them comparable

Comparing this optimized system with a regular transmission that utilizes only a disk as a central rotating element, the increase of the average torque was 42.8 %, the increase of the peak torque was 9.53 %, while the range of the unit and all of other components remained the same.

An experimental setup was developed to test the transmission with different geometries. The results showed high correlation with the simulated model behavior, where the difference between the simulated and measured values of the central disk orientation and the cable positions were under 1.6 %.

3 Developing an optimized trajectory tracking controller - Pure Pursuit Trajectory Tracking

Navigation is one of the most important research areas for wheeled mobile robots (WMRs). Trajectory planning and tracking are common autonomous motion control problems for navigation in known and unknown environments. Trajectory planning is a task of generating appropriate path, which is an explicit function of time to reach a particular location while avoiding collision with obstacles. Trajectory tracking is a task of autonomously driving the robot along the planned path by continuously commanding the robot with calculated speeds that compensate the tracking errors.

The geometric-based pure pursuit method is based on commanding a robot to follow a curve that connects the actual and the goal position on the reference path which is a fixed distance ahead. Obviously, the original pure pursuit method is a pure path tracking method which does not include the time required to accomplish this path. So, in order to make it a feasible and reliable trajectory tracking method that can consider the execution time and can cope with the velocity and acceleration constraints imposed by the robot, another approach is needed which is the contribution of this work. In the developed approach here, the fixed lookahead distance is radically changed to be an updating time dependant lookahead distance considering the planned trajectory which is implicitly satisfying those constraints. Namely, the developed approach calculates a lookahead distance between the current and the desired position of the robot on the planned trajectory after n time steps, which can be determined based on achieving both the robot stability and high accuracy tracking errors. From this time dependent lookahead distance, the curvature of a circular arc connecting those two positions can be determined and thus the commanded linear speeds of the wheels can be calculated in real-time see Fig. (3).

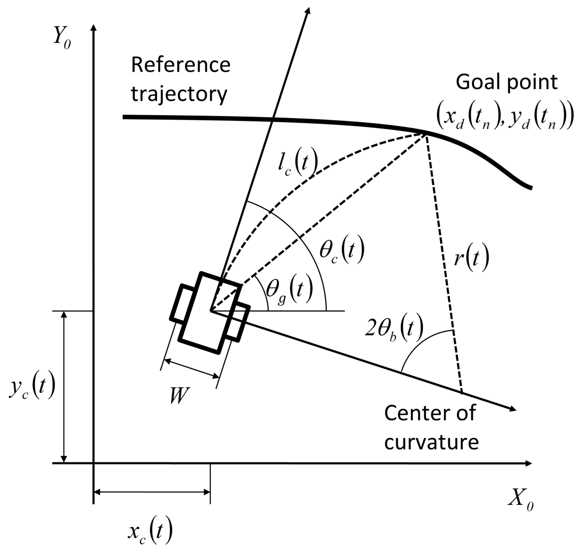

Figure 3: The geometry of the algorithm of the developed pure pursuit method

Therefore, the developed approach makes the original one a real-time trajectory tracking approach that can achieve high accuracy tracking errors with high reliability, and thus it can compete with the commonly used state tracking controllers. Moreover, the developed method avoids the selection of the tuning and damping parameters used by those well-known state tracking controllers.

The algorithm of the whole developed pure pursuit trajectory tracking approach for one segment is given as follows:

1. Plan a trajectory using the trajectory planner to get $\mathbf{q}_d(t_n)$ and the minimum time for a trajectory segment (f)

2. While $t \leq f$

    (a) calculate $\mathbf{q}_d(t_n)$

    (b) calculate $v_r(t)$ and $v_l(t)$

(c) command the robot with 'Set Speed' command ($v_r(t)$, $v_l(t)$)

(d) update odometry

(e) update sampling time

3. end

Experiments have been conducted on the differential-drive mobile robot Koala II. The trajectory tracking was executed repeatedly using the feedforward method, the state tracking methods both linear and nonlinear and the developed pure pursuit method. As a result, the newly developed approach reached less than one fifth of the positional and orientational error on the test trajectory relative to the state tracking methods.

4 Implementation and validation of a new fuzzy arithmetic concept

Fuzzy control is a control process based on fuzzy logic. It operates with analog values throughout the whole computational cycle using fuzzy membership functions instead of binary values.

Similarly to other controller types, an essential part is the connection with the outside world through inputs (X) and outputs (Y). The communication is carried out by real numbers, thus simplifying the controller integration into a bigger system.

A fuzzy linguistic variable or membership function translates an exact input (x) into the world of fuzzy. A general membership function is the following: $\mu : X \to [0,1]$, which represents the truth of a given $x \in X$ for a given μ membership function. If an input x is well represented by μ, then μ will map x around 1 and also if x is not a typical member of μ, then the result will be near 0. On the output of a Mamdani type fuzzy controller, similar membership functions are declared to define the final output membership function of the controller, which represents the overall output.

In the heart of the fuzzy controller, there are rules connecting the inputs with the outputs. A fuzzy rule base is consisting of r rules with the following form:

$$IF\ x_1\ IS\ P_s^1, x_2\ IS\ P_s^2, \ldots, x_m\ IS\ P_s^m\ THEN\ y\ IS\ Q_s,$$

where P_s^l (and Q_s) are linguistic values of variable X_l (and Y), and $x = [x_1, x_2, \ldots, x_m]$ are the input values ($s = 1, \ldots, r$ and $l = 1, \ldots, m$).

To operate a fuzzy controller, the defined rule base has to be evaluated, with the previously introduced 'IF ... THEN ...' form of the rules. The 'IF ...' part is also known as the antecedent, while the 'THEN ...' part is called consequent. During the operation, first all r rules antecedents must be evaluated. An antecedent consists of one or more membership functions combined with fuzzy operations, usually 'AND', 'OR', or 'NOT'. Since the classical implementation of these operations are *min*, *max*, and $(1-x)$, this task is usually computationally efficient. As a result, the fitness or the truth value of each rule is calculated for any given x input.

This truth value is propagated to the consequents during the implication operation. The classical implementation of it can be carried out by the *min* function. The result of this calculation is the rule base r consequents with the assigned fitness values of the corresponding antecedents. In theory, the consequents can also be defined as a complex combination of membership functions but in practice, they usually consists of only one such function.

The next step is to generate the output by a complex membership function ($A(y)$) using the previously gathered implied consequents. This process is classically called as aggregation, and usually implemented by the *max* mathematical function.

The final step is to calculate the most representing element (y^*) of the output membership function. This process gives a real value for each Y output, hence the name of the operation is called defuzzification. One of the best defuzzification technique, therefore the most widely used one is the center of gravity (COG), which can be obtained by calculating the weighted integration. In case of general membership functions, this can only be approximated numerically which requires that both the implication and the aggregation must be carried out numerically as well. As a result, these steps are computationally intensive and only approximations.

Based on József Dombi fuzzy arithmetic theories, where operations are carried out on the inverse functions, a computationally efficient technique was implemented.

In case of triangular and trapezoid membership functions, the process is introduced as arithmetic based control (ABC), while for the sigmoid functions, it is called Pliant control.

Both new methods are based on simple arithmetic operations instead of implication. Furthermore, two new defuzzification operations were also introduced. These new fuzzy controllers can vastly outperform the classical approach in accuracy and speed, while they are also range independent and they can intuitively handle different levels of fuzziness.

The main advantages in using the ABC or the Pliant method are the followings. The general problem of classical Mamdani method with COG defuzzification is the range dependency which often causes designing error. This occurs when the center of a membership function is defined at the edge of the range. However, the output is not affected by the range with the ABC method, therefore the membership function will be precisely defuzzified.

When membership functions with different level of fuzziness need to be defuzzified, the classical COG method will shift the defuzzified value, because it prefers the higher level of fuzziness. In the contrary, ABC and Pliant methods intuitively consider the validities of all membership functions.

In contrast to the Pliant and ABC methods, the classical COG requires numerical integration as part of the calculation, which explains the high difference in accuracy and speed between the classical and the proposed methods. The result of the comparisons showed, if the numerical resolution is low ($n = 101$), the speed is 15 times faster. If the resolution is medium ($n = 1001$), the speed is 190 times faster. If the resolution is high ($n = 10001$), the speed is 2400 times faster.

Genetic algorithm based optimization can also be successfully applied to the proposed fuzzy controllers in order to boost the performance. To achieve this, redesigning of the rules and membership functions are required. The error of the optimized Pliant controller was significantly reduced using the MATLAB water tank demo, if the number of the rules were not changed. However, in the inverted pendulum demo, inspite the fact that the optimized controller could use only two rules, the sum of the absolute error was still lower compared with the classical controller using 16 rules.

5 Summary of the new results

5.1 Thesis 1. Optimizing the transfer function and designing a new force to torque transmission system for pneumatic artificial muscle (PAM) actuator

I developed a new model using six parameters capable of modeling the static characteristics of PAM actuators which expresses the generated force as a function of contraction and pressure. This function further improved the compactness and precision compared to other compact models. This function is especially useful in the usual working range of the PAMs, because of its lower error rate. Furthermore, the reduced number of parameters allows faster and more reliable model fitting. Its inverse function is also capable to express the pressure required to maintain a given contraction with a given force which is necessary for open-looped applications. I also proposed a recalibration method, in which only a limited number of measurements are required to refit the model with remarkable precision.

I also developed a simulation framework which is capable to optimize nonlinear transmission systems with various characteristics. I designed a new non-circular shaped pulley which can improve the efficiency of the force to torque transmission in an antagonistic setup of PAM actuators. I also designed an experimental transmission unit to validate the capabilities of the theoretical results, which showed significant improvements.

I measured the gear reduction capabilities of the physical model as well and my results showed high correlation with the simulated model behavior.

5.2 Thesis 2. Developing an optimized trajectory tracking controller - Pure Pursuit Trajectory Tracking

I developed a new concept for the trajectory tracking for differential-drive mobile robots, in which an updating time dependent lookahead distance related to the sampling time was introduced. The developed method also avoids the selection of the tuning and damping parameters used by the well known linear and nonlinear state tracking controllers. In the contrary, my controller requires only one application and device independent parameter.

I implemented my concept to a mobile robot and compared it to the commonly used linear and nonlinear state tracking controllers. As a result, significant tracking error reductions and a high reliability had been obtained by the developed method which outperforms the other tracking controllers.

5.3 Thesis 3. Implementation and validation of a new fuzzy arithmetic concept

Using the fuzzy arithmetic theories of József Dombi, I developed a fuzzy controller which can be used in practical MATLAB simulations as well. I implemented for the first time, the frameworks for the whole Pliant and ABC fuzzy control in MATLAB environment. Furthermore, I also implemented new fuzzy structures in these frameworks for controlling typical demo systems, and compared their performance to the classical fuzzy controller.

I showed that the implemented system outperforms the classical fuzzy controller in accuracy and speed. It is also range independent and intuitively handles different levels of fuzziness.

I also applied genetic algorithm based optimization to the proposed fuzzy controller in order to boost the performance.

6 List of publications related to the thesis

The contribution of the author to the thesises are summarized in table (1).

Table 1: Thesis groups and the corresponding articles

	[1]	[2]	[3]	[4]	[5]
I.	•	•			
II.			•		
III.				•	•

References

[1] **T. Szepe**. Accurate force function approximation for pneumatic artificial muscles. *Logistics and Industrial Informatics (LINDI). 3rd IEEE International Symposium on IEEE, Budapest, Hungary*, 2011.

[2] **Tamás Szépe**. Optimizing torque characteristic of antagonistic PAM actuators with a nonlinear torque transmission. *Advanced Robotics - publication under review*.

[3] **Tamas Szepe**; Samy F.M. Assal. Pure Pursuit Trajectory Tracking Approach: Comparison and Experimental Validation. *International Journal of Robotics and Automation, Acta Press*, Vol. 27(4), pp. 355–363, 2012.

[4] József Dombi, **Tamás Szépe**. Pliant control system: implementation. *Intelligent Systems and Informatics (SISY)*, 8, 2010.

[5] József Dombi, **Tamás Szépe**. Fuzzy Control Revisited. *PLOS ONE - publication under review*.

Further related publications of the author

[6] **Tamás Szépe**, József Sárosi. Matlab Models for Pneumatic Artificial Muscles. *Scientific Bulletin of the "Politehnica" University of Timisoara, Romania Transactions on Mechanics*, pp. 65–70, 2009.

[7] **Tamás Szépe**. Sensor Based Control of an Autonomous Wheeled Mobile Robot. *Proceedings from PROSENSE Seminar Presentations, Ljubljana*, 2009.

[8] **T. Szepe**, J. Sarosi. Model Based Open Looped Position Control of PAM Actuator *IEEE 8th International Symposium on Intelligent Systems and Informatics, Subotica, Serbia*, 2010.

[9] Sárosi J., **Szépe T.**, Gyeviki J. Approximation Algorithm for the Force of Pneumatic Artificial Muscles. *Proceedings of Factory Automation, Kecskemét, Hungary*, pp. 101–104, 2010.

[10] Sárosi J., **Szépe T.**, Gyeviki J. Function Approximation for the Force Generated by Different Fluid Muscles. *Analecta Technica Szegedinensia, Review of Faculty of Engineering*, 1, pp. 75–80, 2010.

[11] Sárosi J., **Szépe T.**, Gyeviki J. New Mathematical Model for Pneumatic Artificial Muscles. *Hungarian Agricultural Engineering*, 22, pp. 49–52, 2010.

[12] Sárosi J., **Szépe T.**, Gyeviki J., Szabó G., Szendrő P. Mathematical Model for Fluid Muscles. *11th International Carpathian Control Conference, Eger, Hungary*, pp. 87–90, 2010.

Other references

[13] Roberts, Adam. The History of Science Fiction. *Palgrave Histories of Literature, Palgrave Macmillan, New York*, pp. 168, 2006.

[14] Poole, Harry H. Types of Robots. *Fundamentals of Robotics Engineering, Springer Netherlands*, pp. 27–51, 1989.

[15] All On Robots website. *http://www.allonrobots.com/types-of-robots.html*

[16] A. Kapelevich High Gear Ratio Epicyclic Drives Analysis. *Gear Technology*, pp. 61–67, 2014.

[17] J.W. Sensinger, J.H. Lipsey. Cycloid vs. harmonic drives for use in high ratio, single stage robotic transmissions. *Proceedings-IEEE International Conference on Robotics and Automation, Minnesota, USA*, 2012.

[18] N. Schmit, O. Masafumi. Design and realization of a non-circular cable spool to synthesize a nonlinear rotational spring. *Advanced Robotics*, Vol. 26, pp. 234–251, 2012.