Intelligent fuzzy-neural pattern generation and control of a quadrupedal bionic inspection robot

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Abstract. This paper represents a case study on ‘single leg single step’ pattern generation and control of quadrupedal bionic robot movement using intelligent fuzzy-neural approaches. The aim is to set up a flip-flop mechanical configuration allowing the robot to move one step forward. The same algorithm can be integrated to develop a full trajectory pattern as an interconnected task of global path planning for autonomous quadrupedal robots.

1. Introduction

The tendency of designing robotic systems based on biomimetics has effectively started with the Arab polymath, Al-Jazari, (1136-1206) with his invention of the musical robotic band working based on hydraulic switching. Since then, engineers continued developing bionic robots and control systems by ‘inhaling’ the massive designs prototypes in the nature.

Robots in construction are adopted not only to automate the construction process, but also to carry out quality management tasks. For instance, flying drones can inspect high-rise structures or can serve to execute photogrammetry. Telerobotic solutions are used to inspect shafts, air conditioning systems, and manholes. Climbing robots are used to inspect bridges, towers and hidden difficult corners of the building. The success of implementing intelligent solutions to carry out the inspection tasks strictly depends on the performance of the robotic control system, the stability and reliability of the design mechanism and the inspected site condition. The latter can create major obstacle for the robot to move. For instance, with the vertical take-off and landing flying robots such as quadrotors, stability tends to minimize when the altitude increases. On the other hand, wet fields paralyze the robot pedal mechanisms.

Recurring to the control methodology of the robot, we can state that synchronization of different end-effector mechanisms is essential to start the movement and thus to track the desired trajectory. For example, a rotorcraft, UAV, has to be controlled so that to produce equivalent rotational speed of a chosen rotors combination in order to shift between four flight regimes: hover, roll, pitch and yaw. For walking robot, legs located on different body axis sides have to work based on a flip-flop regime in order to shift the center of gravity of the robot and to make it move from its current position. These regimes are called patterns. In our paper, we discuss a quadrupedal robot, performing inspection of glass facades. The study will be limited to a mathematical model of the locomotion end effectors, global path planning control based on prototype patterns. The results are simulation graphs depicting the performance of tracking the generated pattern trajectory.
2. Walking as a technical bionic task

In the engineering concept, movement is realized via mechanisms, which generate lift forces and torques. The end effector, which interacts with the surrounding, can be tires, chains, and propellers etc. For walking mechanisms, the concept is different- a “foot” is touching the ground. The walking mechanism is minimally divided into three mechanical parts. It can reach higher grades of complexity depending on the manoeuvres, which are required to be accomplished and degrees of movement freedom. While walking, the end effector exerts forces parallel to the main movement axis. As a result, the mechanism will act as a pendulum. The frequency of harmonic oscillation of the mechanism depends on the walking speed.

Although it can be divided into smaller functional components, the walking process is presented as a single input-single output system. It is not wise to adopt a multiple systems approach as it is not optimal to use from the point of view of dynamics, feedback control and signals analysis. In the wake of the above-mentioned, it is not so important to study how a separate component works, but how it can integrate with other components and how it is going to influence the overall performance of the consolidated system. This technical task is topical from the point of view of robotics, and it can be categorized under swarm control, where swarm designates the combination of different mechanisms working in the adaptive synchronized regime in order to achieve a global control task. Based on bionic researches, the walking process is categorized as anticipatory feed-forward (proactive) regulation. It is the case of the most repetitive behaviour reacting to external stimuli. More complex walking systems comprise more complex stimulation generation and coordination control. This rhythmic dynamics is known also as central pattern control (figure 1).

Figure 1. The structure of central pattern control for the quadrupedal robot.

In figure 1, the following parameters are depicted: neurons with index 1-3 are motor neurons, where neurons 1 and 2 are used to steer right and left, neuron 4 is sensory, and C1 to C4 are intermediate neurons. Arrows represent an excitatory connection and the point arrows are for inhibitory connection. As it can be seen, it exist inhibitory connection between C1 and C3 thus allowing the oscillation pattern to be generated. The synchronization between legs movement known as periodic gait requires rules and timing control, otherwise inhibited legs will act as ‘car-break’. Consequently, the smoothness of the walking process is not achieved and a possible damage to the mechanical parts is forecasted. The general combination of possible gaits for a mobile robot is calculated as follows:

\[ N_G = (2n - 1)! \]  

where \( N_G \) – the possible number of gaits for a given robot and \( n \) – the number of legs of the robots; in our case, \( n = 4 \).

3. Control of a bionic leg

The most optimal control strategy from the stability perspective is to have the local controller for each leg separately and then to generalize the flip-flop rules according to periodic gaits. This cyclic coordination is necessary in order to obtain smooth and natural oscillation of the mechanical part. This will reduce the energy consumption, as the oscillation will be obtained with no power prerequisites. The other benefit of this approach is to minimize the wear and tear frequency of the mechanical parts as there is no need for any breaks and break releasing mechanisms. Beside synchronization and periodic gait control, posture control is essential for safe movement. By posture control, we understand the ability of the control system to maintain the centre of mass of the
leg in a controllable stable diapason. From the design point of view, the centre of mass geometric point should be within the geometric focus point and the body, thus allowing the robot for better manoeuvrability in case of crosswind. This is essential when having the robot moving at high altitudes.

As a consequence, the global control task for the walking robot includes the following subtasks:

a. Stance control is associated with the kinematic configuration of the legs;
b. Posture control is responsible for centering of the mass position and mostly studied with dynamic analysis;
c. Swing control overlooks the frequency synchronization between different mechanisms in accordance with the first two approaches.

3.1. Literature review

The most optimal control aspect of walking robots cannot be perfectly liaised with natural processes, as the latter is extremely difficult to copy and far more complex than the task of reverse engineering. In addition, the natural biological tissues react somehow differently to exerted forces and applied moments. Nevertheless, different studies were oriented to incorporate the biological concept to the control system of the walking robots. For instance, [3] suggested decentralized control for a top-to-down hierarchy system. The behaviour of the mechanical components of the walking system was studied in depth. In [6], the author studied the topic from the point of view of a central pattern generator. Although the single leg control approach was adopted, they have analysed further the implementation of an oscillatory pacemaker regulating the period of activation of each leg.

Regarding the stance control, the literature analysis reflects the complexity of the task, as it requires real-time monitoring, reading of angular and position sensors and computation of regulating voltage. For a small mobile robot, the on-board microcomputer is not optimal when the stance problem is targeted. This will cause a slow walking process, and it can be treated as a local minimum task as the robot evaluates all possible outcomes of the control algorithm. Taking into consideration that robots are moving in unknown and risky environment, the average of data to be analysed is tremendously huge for on-board electronics.

Pertaining the swing control, the task is far simpler than the previous task as it is mechanically detached from the axis-body of the robot. In [3,7], the authors suggested two-layer designs of the feed-forward neural network with six inputs and two outputs representing the angular velocity of each mechanical joint.

As a conclusion of the literature review and, particularly, of [1-5], the three control subtasks were re-identified. The global control problem of the walking mechanism encompasses the following tasks:

a. Centre of the mass position and speed control;
b. Gait control according to the central pattern generator;
c. Single leg control including the stance, swing and obstacle avoidance;
d. Direction control and steering of each leg with reference to the global trajectory;
e. Control of internal components affecting the excitation and inhibition of a chosen leg.

3.2. Quadrupedal Robot Model

Modelling and control of legged robots is a topical technical problem. Many researchers from different scientific backgrounds combine their efforts on a regular basis in order to obtain an adequate mathematical model. As it was cited earlier, the simplest approach is to adopt decentralized control for each modelled leg of the robot taking into consideration a central pattern generator. This can be explained as follows: to walk, human being defines his orientation based on the need (desired trajectory), communicates and formulates this need into pulses (central generator), transfers the message to the local control post (decentralized controller), which imposes certain behaviour on the end-effector. The same idea is applicable in case of the bionic robot. The structural diagram of the decentralized control task with reference to the central pattern generator is depicted in figure 2. As it can be noted, the desired moment for each leg is obtained from the pattern registrar as desired torque.
\( \tau_d \), the output is the torque applied to load \( \tau_l \), where the latter is being modulated via the motor rotational velocity as indicated in the following equation:

\[
\omega_M = \tau_l \left( \frac{1}{J_l} p + \frac{p}{K_{st}} \right),
\]

(2)

where \( \omega_M \) — the motor angular velocity; \( J_l \) — the load inertia; \( p \) — the Laplace operator and \( K_{st} \) — the stiffness coefficient.

On the other hand, the torque exerted by a spring caused by angular deflection is computed as follows:

\[
\tau_l = -K_{st} (\theta_l - \theta_M),
\]

(3)

where \( (\theta_l - \theta_M) \) represents the deflection between the motor and the load.

**Figure 2.** The simulink model of decentralized leg control.

It is easy to find the motor torque using the motor angular velocity, which in its turn can be found from the angular position. Therefore, it is possible to write the following equation:

\[
\omega_M = \frac{\tau_l}{K_{st} p + \theta_l p};
\]

(4)

As it can be seen from (4), the term of inertia in rotational moment \( J_l \) does not appear in the right-hand side of the equation. Taking figure 3 as a reference point, it can be noted that equation (4) is being compensated using the feed-forward approach, where the PD transfer function represents the uncertainty compensation, which is added to the mechanical interference and fed to the motor controller as a single input equal to desired rotational velocity of the motor. In the wake of the above-mentioned, it is obvious that the position of the leg (stance control) is not crucial for the swing mechanism, thus the control task is formulated as a velocity-based approach. Randomly, we have chosen the numerical values of the parameters highlighted in the aforementioned equations. The task is to achieve

**Figure 3.** Simulation results of the decentralized leg control: \( x \)-axis: time, \( [s] \), \( y \)-axis: torque \( [Nm] \)
3.3. Fuzzy Logic Pattern Generator

Let us study the gait of a quadrupedal animal and try to implement the same pattern in the mobile robot. Figure 4 illustrates the pattern combination of each leg. We define eight working elements as each leg consists of two mobile sections: the upper part (U) rotating with reference to the fixed body axis and the bottom part (B) rotating with reference to the upper part. As we can see from figure 5, the three cinematic snapshots have a single result as an output: moving the right front leg (RU2, RB2) one step forward and, consequently, the leg (RU1, RB1) is also moving. To achieve that, the decentralized control system for each leg should follow pattern rules, which are summarized in table 1 for ‘single leg single step’ movement.

**Figure 4.** ‘Single leg single step’ movement representation

| Leg Section | Phase 1 | Phase 2 | Phase 3 |
|-------------|---------|---------|---------|
| LU1         | 1       | 1       | 1       |
| LB1         | 1       | 1       | 0       |
| RU1         | 0       | 0       | 1       |
| RB1         | 0       | 0       | 1       |
| LU2         | 0       | 0       | 0       |
| LB2         | 0       | 0       | 0       |
| RU2         | 1       | 1       | 1       |
| RB2         | 1       | 1       | 1       |

The coloured filling in table 1 represents the activation of the end effector mechanism. For instance, in the first phase, the upper and bottom sections of the left leg (1) and right leg (2) are activated, whereas the right leg (1) and the left leg (2) are inhibited. The same can be represented in a binary form in order set up linguistic rules for the fuzzy logic pattern generator, the design of which incorporates the following steps:

a. Eight inputs with a two membership function representing the gait of each leg section;
b. Four outputs representing in detail the activation and inhibition status of each leg, serving as an input for the swing control.
c. Fuzzy rules representing the possible linguistic combination

The functional block diagram of the swing control system with reference to the fuzzy logic pattern generator can be consolidated as shown in figure 5.

**Figure 5.** The consolidated swing control functional block diagram

D(t) – desired trajectory; FLPG - Fuzzy Logic Pattern Generator; PDC – PD Compensator; NNMC – Neural Network Motor Controller; MI – Mechanical Interference; $K_{st}$ – Stiffness coefficient
3.3. Neural network motor controller
In this paragraph, we discuss the optimization of the motor controller in order to avoid overshoots in velocity. This is necessary as it will allow for better manoeuvrability of the robot and obstacle avoidance as well as minimizing the mechanical interference. The implementation of the neural network is straightforward. Data collected from the PID motor controller will serve to evaluate and train the nonlinear autoregressive neural network with an exogenous input taking into consideration the desired output and the mechanical effect on the leg section. Figures 6a and 6b illustrate the simulation results of the control approach.

![Figure 6a](image1.png)  
*Figure 6a. Control of legs L1 and R1 according to FLP: x-axis: time, [s], y-axis: torque [Nm]*

![Figure 6b](image2.png)  
*Figure 6b. Control of legs L2 and R2 according to FLP: x-axis: time, [s], y-axis: torque [Nm]*

4. Conclusion
The results shown in figures 6a and 6b can be understood as follows: according to the generated pattern developed by the fuzzy logic pattern generator, a combination of end-effectors movements of the quadrupedal robot are assigned as a control task. The monitoring and regulation of the end-effector outputs is managed by the neural network controller. As we can see, the leg systems successfully switch between excitation and inhibition states of leg sections allowing legs R1 and R2 to move one step forward in three phases. It is noticed as well the absence of overshooting.

On the other hand, we can clearly see that the process time has increased from 1.5 s to 3.5 s. This fact is due to the time needed for a fuzzy logic pattern generator to analyze the posture and stance control feedback. Accordingly, the neural network response time is considered in the slippage time. This proves the hypothesis stated earlier about computation time and capabilities of the robot autopilot. Taking into consideration random coefficient parameters, we can clearly see that moving the R1 and R2 legs consumed 15 s in total. This crossed distance estimated is proportional to the specifications of the end-effector (length, mass etc...). The response time can be slightly improved when optimizing the stiffness coefficient of the articulations.

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