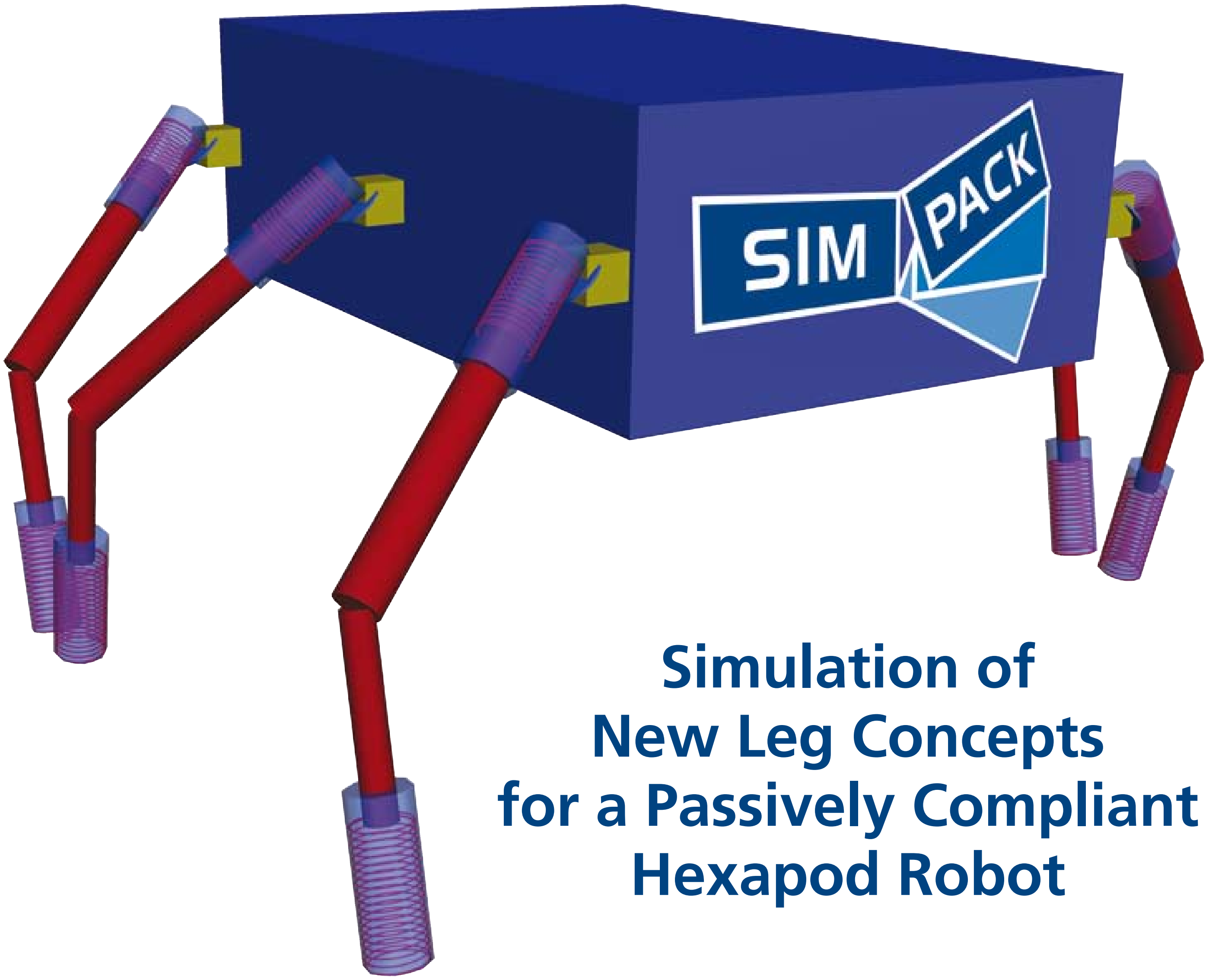
Luca Fiorio, Martin Görner, Armin Wedler,
DLR German Aerospace Center, Institute of Robotics and Mechatronics



Simulation of New Leg Concepts for a Passively Compliant Hexapod Robot

For many years, robotics has drawn inspiration from nature, but only recently has an understanding of the musculoskeletal dynamics of an animal running led to successful designs of small, self-stabilizing legged robots.

Motivated by the question of how robots can take advantage of passive elastic elements, this work explores if considerable mechanical compliance contributes significantly to the stability and the robustness of multi-legged robotic running. For this purpose, three passive elastic leg concepts with increasing complexity have been developed and tested using a MATLAB® - SIMPACK co-simulation.

INTRODUCTION

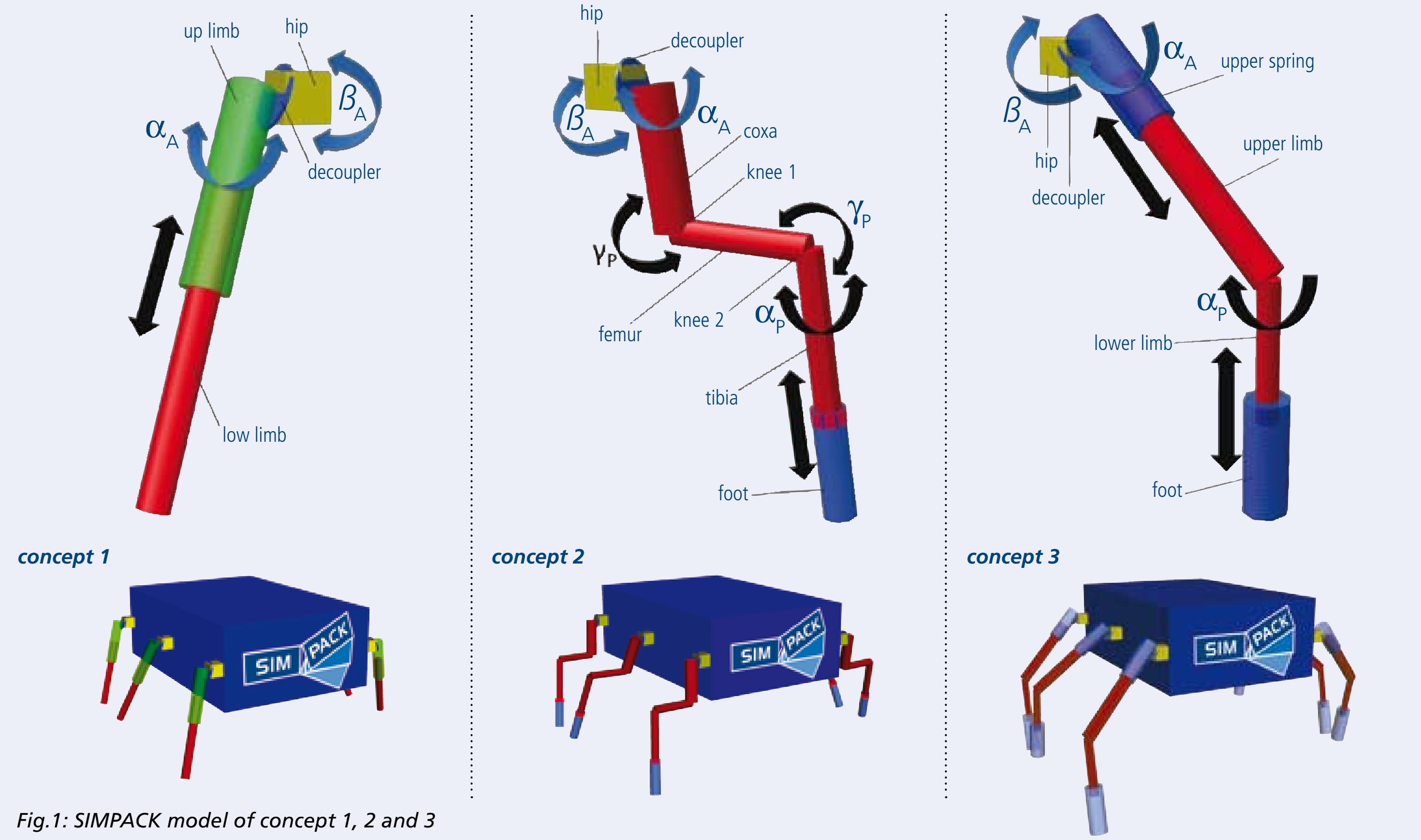
The use of legs for locomotion through rough terrain promises superior performance in comparison to wheeled vehicles. Nevertheless, most of today's legged machines lack a thorough design that incorporates spring elements in order to achieve elastic behavior. To build a robot which is able to walk and run smoothly, even on rough terrain, new biologically inspired leg concepts need to be developed. Those new legs should have the capability to absorb impacts, to store energy within their elastic elements and to change their stiffness, but to some degree should still allow a dexterous foot placement. Exploiting the benefits of passive compliance is the incentive that directs the research concerning the implementation of elastic systems to replace motors and gears within distinct joints. One of DLR's research goals is to show, using simulation studies, that an appropriately designed self-stabilizing structure can ease the control and improve the performance of running robots. This research will result in a deeper understanding of elastic multi-legged robots and will guide further experimental and analytical research.

CHALLENGES

The purpose of this study is to gain knowledge about how to combine actuated and passive elastic joints within a leg such that they enable a hexapedal robot to run stably over a broad range of velocities. Furthermore, it is important to analyze the behavior with respect to its energetics, investigating the possibility of energy recovery during each step. It is well documented that insects, mammals and humans are able to store a certain amount of kinetic and potential energy and release it triggering a complex and continuous exchange of power. Since this phenomenon increases the efficiency of the leg, the use of springs in some proper joints potentially makes the hexapod robot less wasteful in energetic terms.

In addtion to the springs, dampers are important for achieving a robust and stable running behavior. Since this study focuses on energy recovery, damping factors are chosen low enough to keep losses at a low level and high enough to provide stability.

Luca Fiorio, Martin Görner, Armin Wedler,
DLR German Aerospace Center, Institute of Robotics and Mechatronics



concept 1

concept 2

concept 3

Fig.1: SIMPACK model of concept 1, 2 and 3

For each of the three leg concepts, hexapod robots are modeled and simulated with different total leg stiffness settings for a variety of velocities. In this way it is possible to investigate the relationship between stiffness and velocity and their influence on energy efficiency.

LEG CONCEPTS

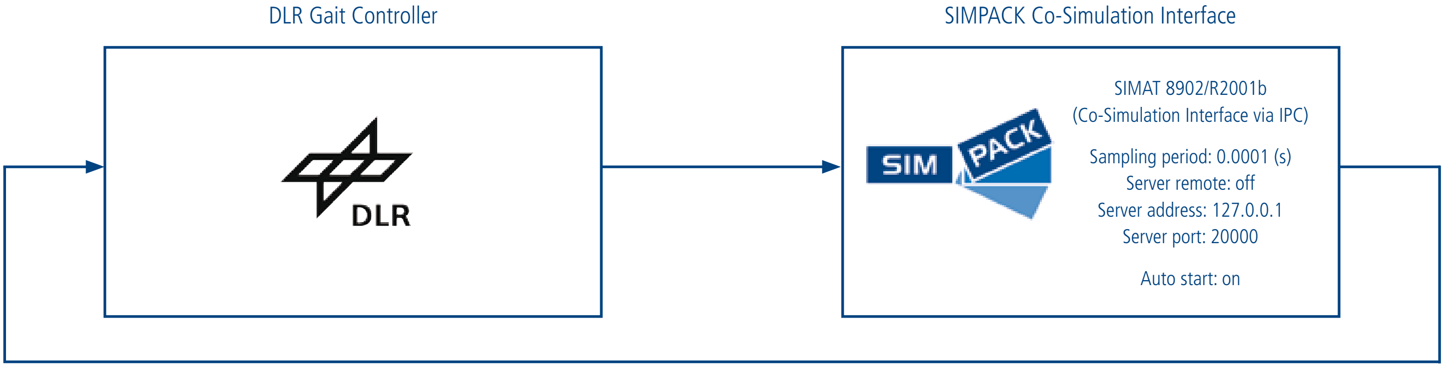
Basically, this work encompasses three different leg types. The first design is inspired by the simplification of the 3D spring-loaded inverted pendulum (SLIP) theory. The second is closer to biological insect legs and the third model captures characteristics from both. For each concept simplifications have been considered in order to obtain a structure that, even while preserving the main features of the ideal model, could easily be controlled with only two actuated degrees-of-freedom.

The main features of the legs are passively compliant elements that allow the leg to absorb energy in one part of the step and to release it in another. The second important aspect of the compliance elements is the reduction of the shock-loads for the main body of the robot which appear during each step when the foot hits the ground. In order to have a light leg, and to reduce the number of motors, only the hip joint of each leg has two actuated degrees-of-freedom.

> **“...the tangential force is calculated using the Coulomb friction...”**

Running at high velocity means high velocity of the limbs and results in high ground impact forces. If the intensity of these vibrations is excessive, it can damage gears and motors. To protect the hip actuators a decoupler was inserted between the leg and the hip (see Fig. 1, concept 1). Those elements were realized using a planar joint controlled by springs and dampers.

The contact between the foot and the ground is modeled as a point contact with



SIMAT 8902/R2001b
(Co-Simulation Interface via IPC)

Sampling period: 0.0001 (s)
Server remote: off
Server address: 127.0.0.1
Server port: 20000

Auto start: on

Fig. 2: SIMAT co-simulation interface

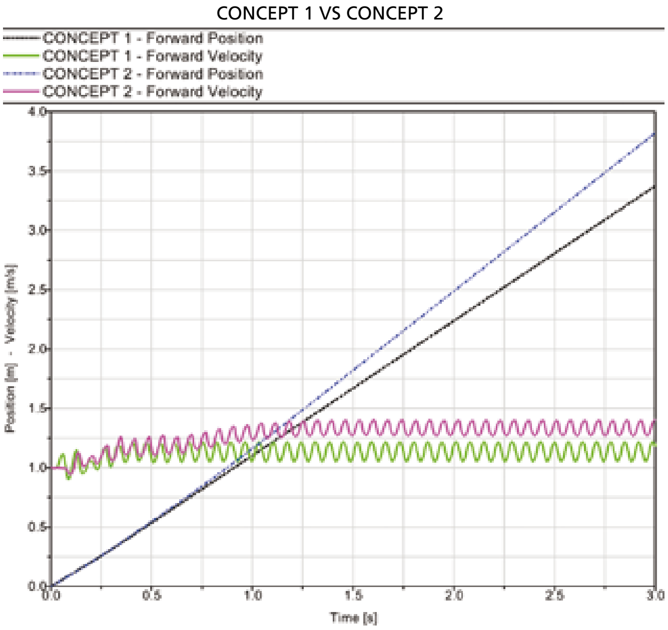


Fig. 3: Comparison of forward position and velocity in concept 1 and concept 2

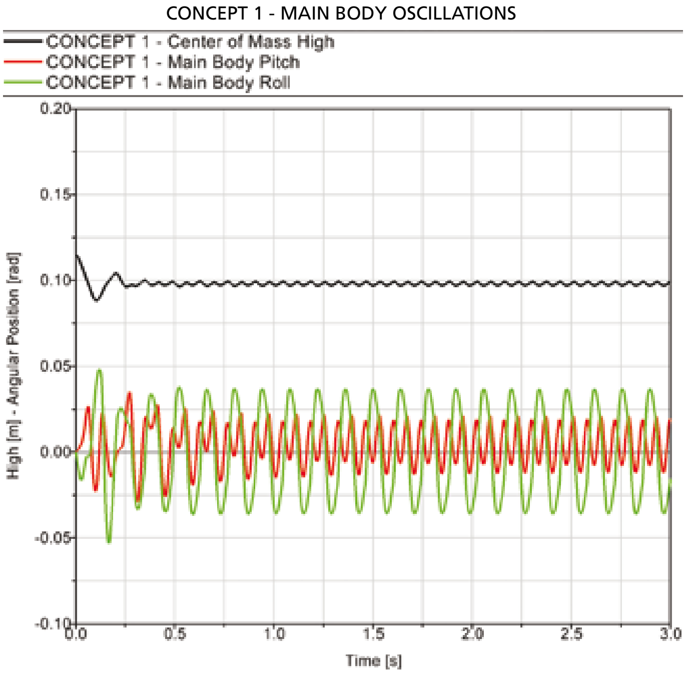


Fig. 4: Oscillations of the main body in concept 1

friction. The normal force is calculated using a unilateral spring-damper system, while the tangential force is calculated using the Coulomb friction coefficient μ_{fr}.

A) Concept 1

This leg model is the most simplistic one because the leg is composed of only two limbs connected with a prismatic joint controlled by a passive spring-damper system. The goal is to have simulations that exploit the SLIP model in a 3D configuration embodying a richer behavior than the planar model. In Fig. 1, concept 1, the active degrees-of-freedom are shown in blue, while the passive are marked in black.

> ***“The simulation also allowed the identification of critical situations.”***

B) Concept 2

This leg concept design is based on biological observations of insects [25]. The main feature of insect legs is their adaptability to different terrain and the ability to run using a fast and simple gait. Those features make the insect leg suitable for use as a template to develop a structure able to satisfy the requirements of a good running hexapod machine.

Fig. 1, concept 2, shows the degrees-of-freedom of the leg. Between femur and coxa a passive rotational joint called ”Knee 1” with only one degree-of-freedom γ is implemented. Tibia and femur are connected with another passive rotational joint called ”Knee 2” with two degrees-of-freedom: γ and α, where the second is intended to better damp impacts of the foot with obstacles on rough terrain. The ”Foot” link is a linear joint that tries to emulate the behavior of the tarsal insect segments.

C) Concept 3

This concept is an intermediate version of the two previous designs. It is more complex than the first case, but simpler than the third. There are again only two limbs, but in this case, they are connected with a rotational joint. In addition, two linear springs were added.

In Fig. 1, concept 3, it is possible to notice the foot that is connected to the leg with a linear spring in order to absorb ground impacts. The lower limb, connected to the upper segment with a rotational joint called ”Knee”, and the upper spring stabilize the body from lateral forces. The knee rotational joint gives the leg a forward-backward degree-of-freedom to damp foot collisions during the step.

SIMULATION SETTINGS

Basically, all the work was done using two different software packages. For the multi-body part of the simulation, SIMPACK was employed. It allowed us to first create a CAD model of a mechanical system and then to simulate the static and dynamic behavior with forces and motions plots. Since the program can be used in co-simulation with MATLAB, this second software played the master role. Through Simulink®; the models for the three concepts were controlled by a simple Central Pattern Generator (CPG).

In this case, SIMPACK's SIMAT co-simulation interface was used, connecting the SIMPACK model through a Simulink S-function that can be used with the controller in a closed-loop circuit as shown in Fig. 2. An important parameter that needs to be defined is the sample time between the model and the controller to regulate the exchange information step. A value of 10^{-4} s was found to be appropriate for the simulations. All values larger than this may cause the simulation to become unstable.

RESULT ANALYSIS

The SIMPACK PostProcessor enables measurements to be exported in different formats. In this case, to investigate the dynamical aspect of the hexapod, the data were imported in MATLAB with a structure file including positions, velocities, torques and forces for the body and all of the legs. A complete analysis of the run is done in order to fully understand the energetic phenomena. The balance between the mechanical energy input and output is investigated with considertion to the work done by the motors, as well as all the dissipation due to dampers, contact friction and impacts. This provides a comparison baseline for the parameter variation studies. It also allows one to investigate how well the robot runs in terms of efficiency and which design changes improve its performance. An important parameter that influences the energy consumption is the coefficient of the dampers in the joints. In this

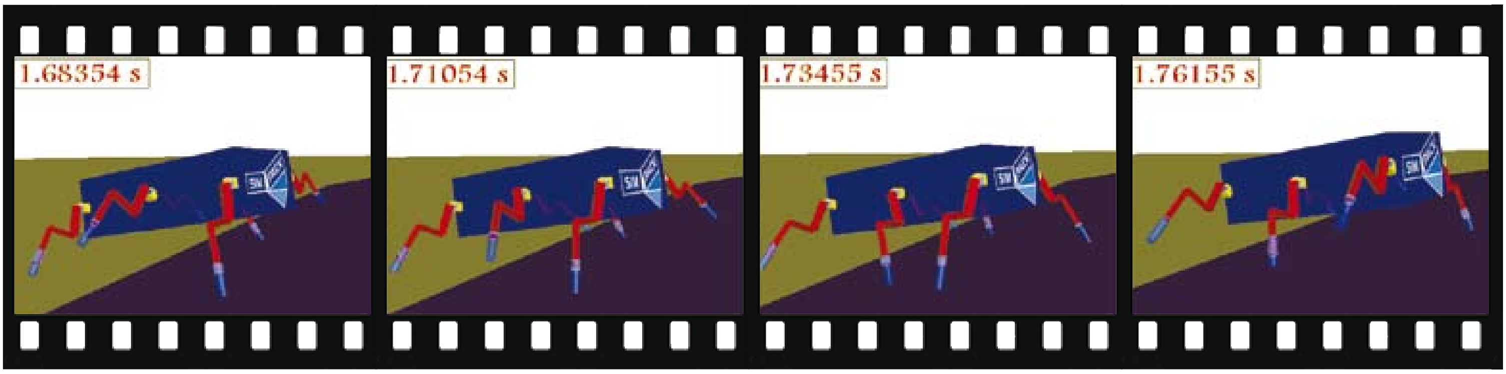


Fig. 4: Video sequence of insect

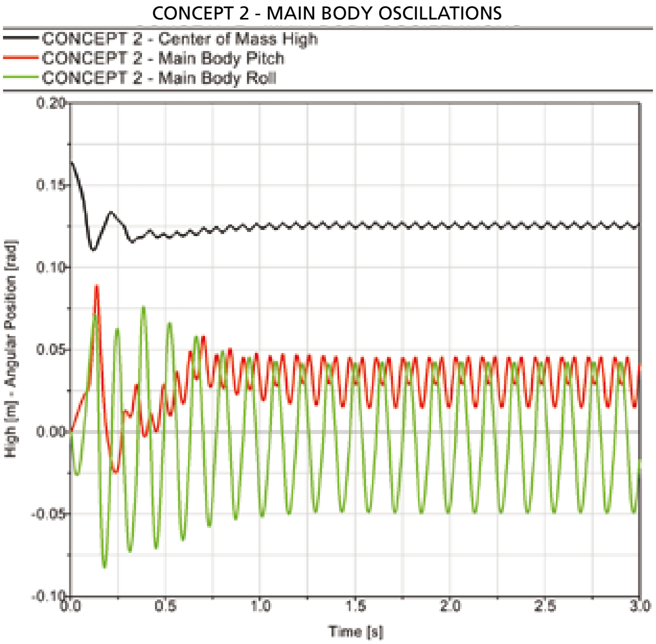


Fig. 6: Oscillations of the main body in concept 2

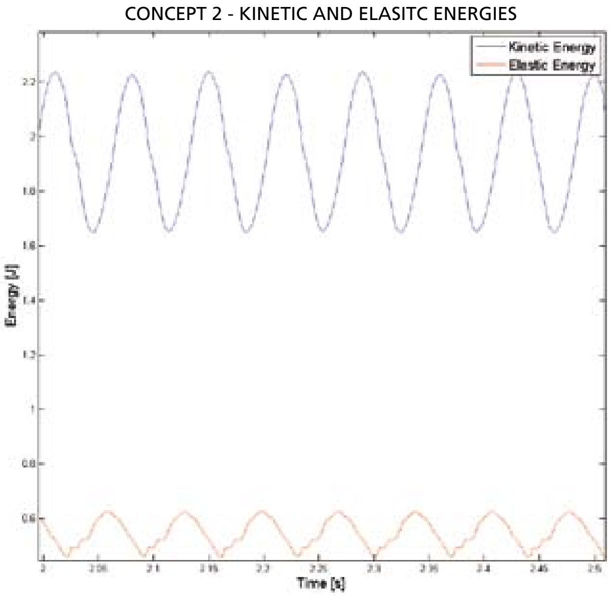


Fig. 7: Kinetic and elastic energies in concept 2

case, it is possible to assume that high values of damping match high energy dissipation. Therefore, this factor was tuned in order to find a good compromise between stability and minimal energy consumption.

OUTCOME

The basic result of this work is to highlight the possibility of building legs that embed spring and dampers within their joints instead of motors and gears. The simulations show that, on flat terrain, the hexapod is able to walk and run smoothly (Fig. 3). Many of these configurations result in fast and self-stabilizing running even though the motion is obtained through a simple open-loop controller that manages only two degrees-of-freedom.

The development of the dynamic simulations of the robot made a rapid virtual examination of the leg parameter space possible, showing the relative importance and effects of the various leg parameters on walking and running speeds. The simulation also allowed the identification of critical situations. The main observation concerning the energetic efficiency was that the legs are not as efficient as expected. It appears that the more rigid systems seem to waste less energy.

This is attributed to the joint dampers which for softer systems show higher activity. On the other hand, this leads to the assumption that the simplified controller was not able to direct the simulated robot towards an appropriate limit cycle, and thus, needs further research. Finding and analyzing the related eigenfrequencies becomes more difficult with increasing mechanical complexity of the legs.

An interesting observation is that basically all models show the transition between walking and running behavior. This becomes evident looking at the phase between kinetic and elastic energies that, like in the SLIP model, are out of phase during running; see Fig. 7.

FUTURE WORK

With current results in mind, there are several directions for future work. These range from the direct application of the simulation-based tuning approach in a real robot to more theoretical questions about the nature of stability when running over rough terrain, and how to appropriately tune the passively self-stabilizing leg of robot.

The next step should also consider the improvement and necessary variability of the gait generator in order to find a simple structure that supports limit cycle behavior of the mechanical system.

Some suggestions have been raised by the current study, but the complex nature of the coupled, non-linear dynamics of the system makes the project open to improvement and poses many interesting questions that need to be answered.