TOWARD CONTROLLED PASSIVE ACTUATION

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ABSTRACT

Experts all over the world agree on the potential of legged locomotion for difficult terrain. As of now, there are several point on which legged machines have significantly lower performance than than wheeled or tracked ones. First of all, they have a *higher number of actuators* which makes them *heavier*. This is related to the mentioned "*low payload to weight ratio*" with is also related to the fact that any additional weight has to be supported by the legs. This (active) supporting of mass, together with the additional movement in the legs compared to wheels and tracks also results in *higher energy consumption*. This energy consumption is further increased due to the fact that energy is lost at every *impact* (say foot touch-down), which also increases the mechanical stress on the entire structure.

In this work a novel, integral approach is presented which minimises the use of electric actuators and enables absorption and re-use of energy involved at impact. By doing this, the number and size of electric actuators is reduced, which reduces the weight. Furthermore, by offering intrinsically passive gravity compensation, the payload capabilities is potentially increased. By minimising the energy flow trough electric actuators, one of the most significant energetic losses is minimised. Our approach uses a single spring to couple two degrees of freedom and therefore energy exchange between two CPA (Controlled Passive Actuation) actuated degrees of freedom.

1. INTRODUCTION

The surveys of (Seeni et al., 2008; Hardarson, 1997) point out several points of low performance of legged locomotion compared to wheeled and tracked locomotion. First of all, they have a *higher number of actuators* which makes them *heavier*. This is related to the mentioned "*low payload to weight ratio*" with is also related to the fact that any additional weight has to be supported by the legs. This (active) supporting of mass, together with the additional movement in the legs compared to wheels and tracks also results in *higher energy consumption*. This energy consumption is further increased due to the fact that energy is lost at every *impact* (say foot touch-down), which also increases the mechanical stress on the entire structure.

The energy involved in an impact can be computed with Eq. 1.

$$E_k = \frac{1}{2} m v^2 \tag{1}$$

It scales linearly with the mass that is involved in the impact and quadratically with the velocity at impact. When aiming at increasing speed capabilities, developments should go in the direction of dynamically stable legged locomotion. The speed of statically stable legged locomotion is limited by the speed at which the limbs can move where dynamically stable legged locomotion does not have this restriction. However, in dynamically stable legged locomotion the kinetic energy of the body and payload as well as the kinetic energy of the limbs contributes to the energy involved at an impact whereas in statically stable locomotion on the the kinetic energy of the limbs is involved. Thus further increasing the stress on the system and the energy losses.

2. RELATED WORK

The quest for improving legged locomotion has been around for decades and the work done in this field is numerous. In this section, an overview is given of related efforts towards this goal in the same direction as this paper. The authors claim by no means that this overview is even close to being complete, its goal is to position the presented work in the context of scientific activity.

Various authors have incorporated compliance in the legs for a number of reasons. The work of (Raby and Orin, 1999) focusses on the energetic benefits from temporarily storing kinetic and/or potential energy. Others, like (Brown and Zeglin, 1998; Scarfogliero et al., 2009) focus more on the absorption and re-use of energy that would otherwise be lost at impact. A completely different approach to addressing problems caused by impacts was found in (Berges and Bowling, 2005) where they investigate how the configuration can help reduce the effects of impacts of the feet.

Furthermore, some interesting work was done on walking robots that run on just one actuator per leg (Cherouvim and Papadopoulos, 2010; Poulakakis et al., 2005), thus reducing the weight of the machine. Here, a compliance in the leg is used to transfer energy. A robot with one actuator per leg was also found in (Balasubramanian et al., 2008) where an approach using a simple but effective wheel-leg hybrid is presented. In addition to using only one actuator per leg their work also utilises a light, compliant leg design.

3. ANALYSIS OF THE ENERGY LOSSES

In the work of (Seeni et al., 2008; Hardarson, 1997) it is pointed out that the increased weight of a legged robot opposed to its wheeled and tracked counterparts is mainly due to the increased number of actuators, where number can be generalised to number and/or size. Furthermore, they mention the relation between impacts and the increased stress that the system experiences. To find a solution for these problems, it seems logical to look in the directions of reducing the amount of actuators and absorbing impact energy. In literature, no explicit cause was suggested for the low energy efficiency, only contributions like active gravity compensation. In this section, the origin of the high losses in legged locomotion and, even, in a generalised robotic setup is analysed.

From an energy-based point of view, energy dissipation, or irreversible transformation, occurs at resistive and damping elements. For a electrically actuated legged robot, the resistive elements in the system can be grouped in electric resistances, mechanical friction and dissipation in the interaction with the environment due to soil compaction and similar phenomena. To illustrate the significance of these losses, a model was constructed of a simple system. The system consists of a motor with gearbox actuating a linear motion of a mass. The model is extended with a simple contact model to illustrate the effect of an impact and it is assumed that energy can be fed-back (recovered) into the system trough the motor. The resulting model structure is presented in Fig. 1.

For this small case study a Maxon motor-gearbox combination is used as specified in Tab. 1. Parameter values are, where available, adopted from Maxon specifications. For model of the friction in the gear-box, a combination of coulomb and viscous friction is used such that efficiency characteristics as described in (Maxon Motor, 2012; Pelchen et al., 2002) is approximated in the working area of the gear-box. For simulation purposes this function has been approximated by a continuous function with parameters r, β, A and B as suggested in (Cull and Tucker, 1999). The motion profile consists of a smooth

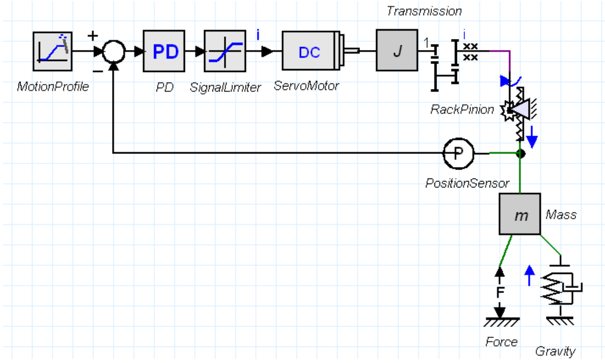

Figure 1: The dynamic model that was used to evaluate the energetic losses. The model contains a detailed motor and gear-box model that drives a mass in the vertical direction. A simple contact model is used to evaluate energy that is dissipated in soil interaction.

up-down motion as shown in Figure 2. Tab. 1 summarises the model parameters that were used to perform the simulation.

Table 1: The model parameters that have been used in the dynamic model to evaluate energetic losses, as shown in Fig. 1.

Component	Parameter	Value
PD	Differential gain	100
	Proportional gain	100
SignalLimiter	Limit	± 7.72
Servomotor (Maxon RE25)	Inductance	$1.15e^{-4}$
	Electric resistance	1.17
	Motor constant	$1.64e^{-4}$
	Rotor inertia	$9.45e^{-5}$
	Friction	$1.156e^{-6}$
Transmission (Macon GP22C)	Gear inertia	$4e^{-6}$
	Friction, r	$4.5e^{-6}$
	Friction, β	$4.5e^{-3}$
	Friction, A	1
	Friction, B	1
	Gear ratio	89
RackPinion	Transformation ratio	$2e^{-2}$
Gravity	Gravitational force	-9.8
Mass	Mass	1
Collision	Compliance	$1e^{-4}$
	Resistance	$1e^{4}$

In the simulation, the energy dissipation in motor, gearbox and soil was monitored together with the energy supply and the energy that was stored in the mass and stiffness elements. Fig. 3 shows the summed results of the simulation. That is, the total amount of supplied, stored and dissipated energy in the system. Fig. 4 and Tab. 2 show the contribution of the three most significant losses to the dissipated energy. 76% of the energy that was dissipated in the system was dissipated in the electric resistance of the motor, another 19% in the gearbox. In order to increase the energy-efficiency of the system, it seems

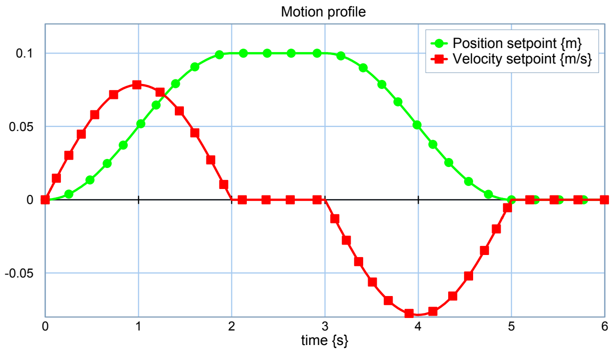

Figure 2: The motion profile that was used to evaluate energetic losses. The profile is a smooth up and downward motion.

logical to look in the direction of minimising the energy flow trough electric actuators.

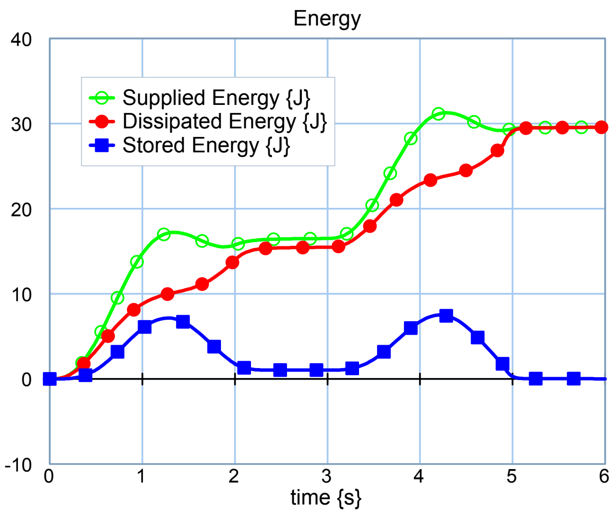

Figure 3: The simulation results of the simulation of the model shown in Fig. 1 with parameters as shown in Tab. 1 and a motion profile as shown in Fig. 2. The chart shows the supplied, dissipated and stored energy in the system during simulation time.

Furthermore, energetic losses due to impact are also clearly present which scaled, as pointed out before linear with the involved mass and quadratic with the velocity at impact. In this case of a statically stable step, the mass involved in the impact is only the mass of the leg. However, in the case of dynamically stable walking, this mass also involves the mass of the robot body, which is significantly higher. Furthermore, when the uncertainty in the terrain increases, the velocity at impact can be expected to be higher. Altogether, it can be expected that the energy losses at impact are in reality higher than in this simulated case.

Based on the simulation that was performed, it is concluded that, in order to improve the energy efficiency, the energy flows through the actuators should be minimised where possible and the energy that would be involved in

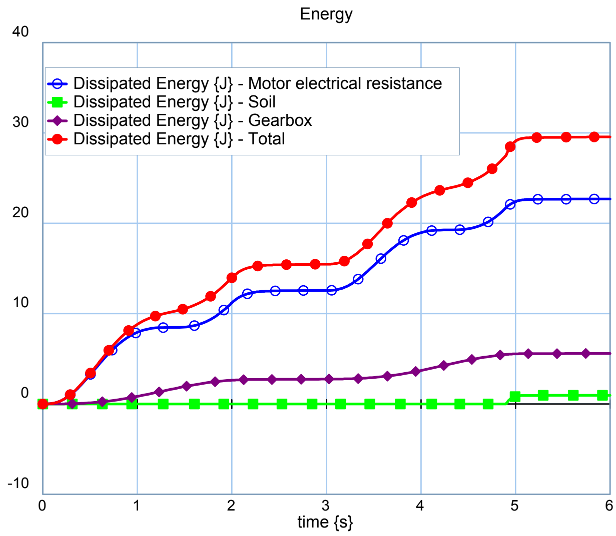

Figure 4: The dissipated energy as shown in Fig. 3, detailed to the origins of energy dissipation. The chart shows de total dissipation, dissipation in the soil, dissipation in the motor electrical resistance and dissipation in the gearbox

Table 2: Relative contributions of the dissipation in the soil, dissipation in the motor electrical resistance and dissipation in the gearbox to the total energy dissipation.

Dissipative element	Loss (% of total losses)
Motor electrical resistance	76%
Gearbox	19%
Soil	3%
Others	2%

impacts should be absorbed where possible.

4. THE PROPOSED APPROACH

Based on the work of (Seeni et al., 2008; Hardarson, 1997) and an analysis of the significance of losses in legged locomotion, the following goals are chosen to tackle the problems in legged locomotion as mentioned in Sec. 1:

- the energy flows through the actuators should be minimised
- energy that would be involved in impacts should be absorbed
- reduce the number and/or size of actuators
- provide passive gravity compensation

As will be shown later in this section, a mechanical spring can form the basis of a design that addresses each of the above goals. Many authors already suggested the use of springs for actuation, either in series with or parallel to an electric actuator (Cherouvim and Papadopoulos, 2010; Poulakakis et al., 2005; Groothuis et al., 2012; Pratt and Williamson, 1995). However, when using springs in series or parallel with an electric actuator, without additional facilities, the actuation by the spring is uncontrollable. In order to be able to control and manipulated the forces that are exerted by the spring, an Infinitely Variable transmission (IVT) can be used in combination with the spring. This has been suggested before in (Stramigioli et al., 2008).

An (ideal) IVT satisfies the following relations:

$$F_1 = rF_2 \tag{2}$$

$$v_2 = rv_1 \tag{3}$$

where r can be any value. It can be seen that, when power port 2, characterised by the conjugate variables F_2 and v_2 is connected to the spring, the force at power port 1, characterised by conjugate variables F_1 and v_1, can be controlled to an arbitrary value by changing the transformation ratio r. When an IVT is properly designed such that

1. the reconfiguration does not change the energy in the system and
2. the reconfiguration actuator should not have to oppose any forces,

the actuator that is used for reconfiguration only needs to overcome some mechanical friction and can be relatively small. The mayor actuation forces, including gravity compensation, can now be applied by the spring in a passive, controlled way. This principle is the key to Controlled Passive Actuation, CPA.

4.1. Impact absorbtion

With the use of springs to provide the main actuation energy, the energy flows trough the actuators are minimised and consequentially the size of the actuators can be reduced. Furthermore, using springs for actuation solves the impact problem by enabling absorption of kinetic energy of objects located "behind" the spring.

To test the potential effect of impact absorption, a second simulation was done as shown in Fig. 5. In this simulation, two masses coupled by a spring with IVT are dropped to experience an impact. "Mass" represents the mass of the robot leg and is chosen $0.01kg$ and "Mass1" represents the, much larger, mass of the robot body. "Mass1" is chosen $1kg$. In the figure, the IVT is represented by a lever of which the pivot-point can be moved freely along the lever. The IVT is used to lock the spring at impact such that the energy is not released right after impact but is stored to be used at a later moment.

To show the effect of the impact absorption, Fig. 6 shows the energy levels and internal forces without impact absorption and Fig. 7 shows the energy levels and internal forces with impact absorption. It can be seen that the impact absorption has two effects: 1) the majority of the kinetic energy involved in the impact is conserved in the spring and 2) the internal forces are reduced significantly. It should be noted that, although this is not clear from the plots, the kinetic energy in the leg can not be absorbed since its located "before" the spring. It is therefore key to design a light leg.

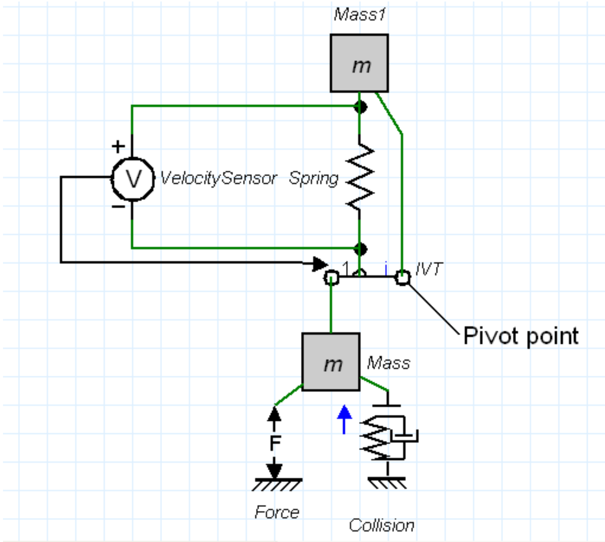

Figure 5: The model that was used to evaluate the effect of impact absorption. It consists of two masses connected by a spring and IVT, where the IVT is represented by a lever of which the pivot point can be moved freely. In includes a simple contact model to simulate ground contact.

4.2. Controlled Passive Actuation

The energy that is absorbed at impact is typically absorbed in the vertical direction while it is preferably used to obtain propulsion in the horizontal direction. For this reaction, the authors believe that, in order to be able to re-use the absorbed energy in a meaningful way, two or more degrees of freedom should be coupled in such a way that absorbed energy can be exchanged. Since a spring is a nodic element it is naturally suitable to couple two degrees of freedom such that a two degree-of-freedom (DOF) CPA can be obtained, where energy can be exchanged between the two DOF's. When coupling this system to a simple two-DOF mass, as shown in Fig. 8.

In the figure, the two IVT's can be found. Each is coupled with one end to the common spring and with the other end to the mass, one for actuation in the x direction and one for actuation in the y direction. Two PD controllers are used to calculate force actuation based on position (and velocity) errors. Based on these force inputs the transformation ratio of the IVT's, r_1 and r_2, can be calculated

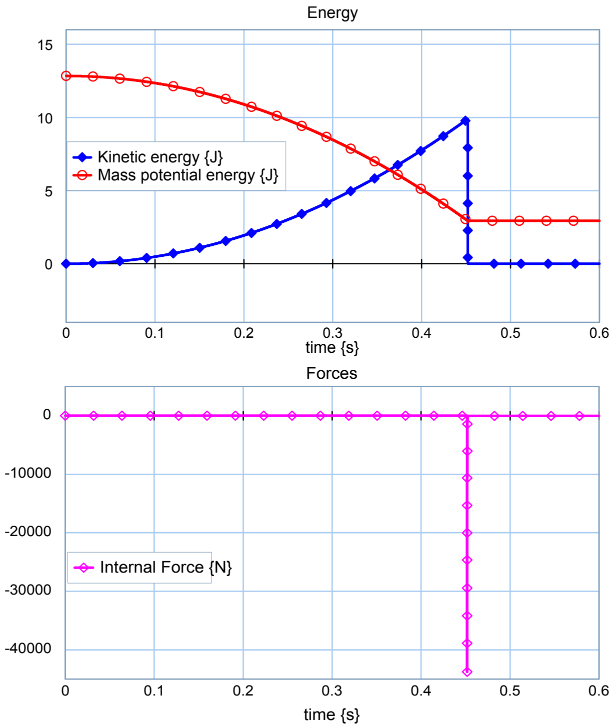

Figure 6: The energy levels and internal forces before, during and after impact in the case that no impact absorption is used. The energy chart shows the total kinetic and potential energy in the system and the force chart shows the internal force that is experienced in the system

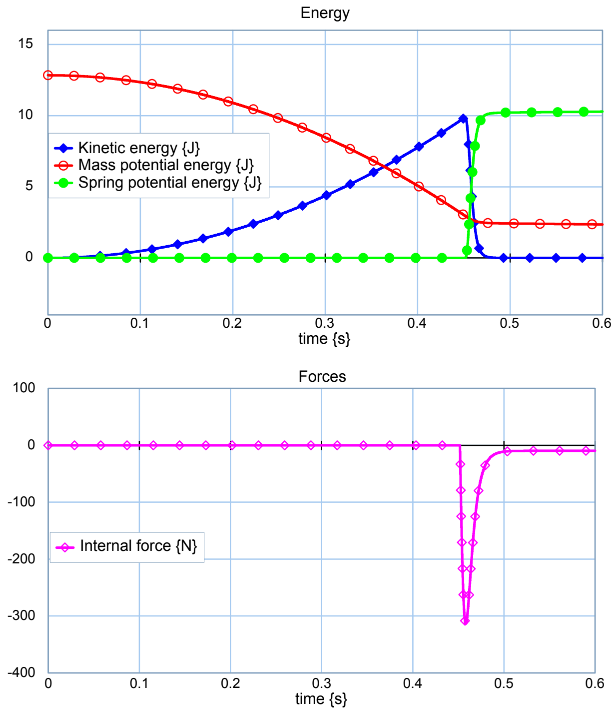

Figure 7: The energy levels and internal forces before, during and after impact in the case that impact absorption is used. The energy chart shows the total kinetic energy, potential energy in the masses and potential energy in the spring. The force chart shows the internal force that is experienced in the system

using the spring state and stiffness with the following reasoning.

The state of an (ideal) spring is the difference between its two end-point positions:

$$x = x_1 - x_2 \tag{4}$$

Expressed in velocities:

$$v = v_1 - v_2 \tag{5}$$

While the exerted force is equal but opposite in sign for the two end-points:

$$F_1 = Kx = K\int(v_1 - v_2)dt \tag{6}$$

$$F_2 = -Kx = K\int(v_2 - v_1)dt \tag{7}$$

With an (ideal) IVT on each end-point, the following relations hold:

$$F_1 = r_1 Kx \tag{8}$$

$$F_2 = -r_2 Kx \tag{9}$$

$$x = \int(r_1 v_1 - r_2 v_2) \tag{10}$$

Since r_1 and r_2 are free to configure, F_1 and F_2 can be determined independent of the state of the spring, x. To obtain desired actuation forces, assuming the state of the spring is measured, r_1 and r_2 can be calculated as:

$$r_1 = \frac{F_1}{Kx} \tag{11}$$

$$r_2 = -\frac{F_2}{Kx} \tag{12}$$

Notice that, for a constant force actuation, the IVT needs continuous adjustment.

To show that such a system is able to perform a controlled actuation in 2D, the system was tested on a step-like motion profile as shown in Fig. 9. The spring is given a non-zero initial condition to provide the system with the energy required for actuation. From Fig. 9 it can be seen that the actuated system is able to follow the set-point with reasonable accuracy.

It should be noted that the IVT's are, of course, mechanical instruments that cannot be reconfigured in infinite time. Therefore, the motion profiles should be of a certain smoothness as can also be seen in Fig. 9. Furthermore, friction has not been incorporated in this simulation yet. In reality, it will of course be present and some energetic losses will occur. This will slowly decrease the amount of energy stored in the system unless this energy is somehow added to the system. This will be a topic of future work.

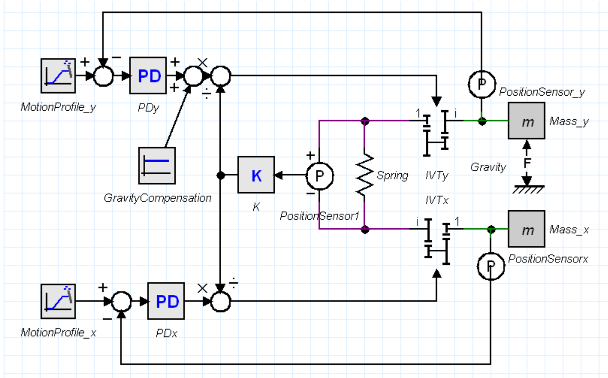

Figure 8: The model that was used to evaluate the CPA concept. The model includes a 2-dimensional mass, two IVT's represented by a transmission, the spring used to store and supply energy, several position sensors and a position controller to control the IVTs appropriately.

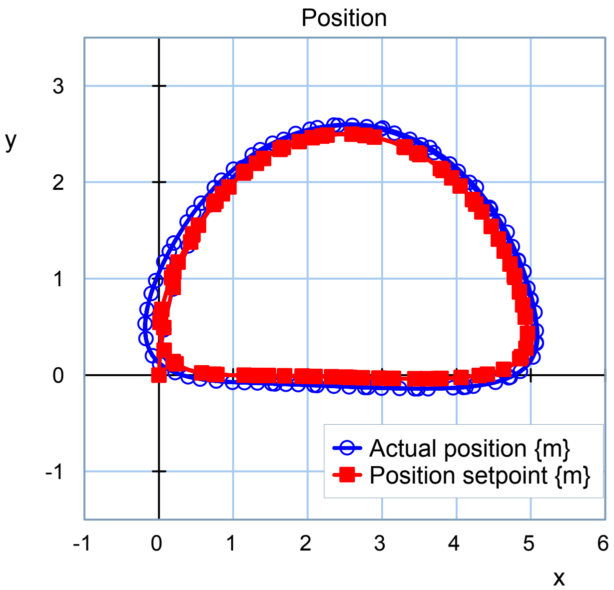

Figure 9: The position set-point and actual position of the CPA-actuated system, as shown in Fig. 8 for several consecutive, step-like motions

5. CONCLUSIONS AND FUTURE WORK

The paper has provided a motivation for a focal point of improvements for legged locomotion, namely 1) the energy flows through the actuators should be minimised, 2) energy that would be involved in impacts should be absorbed, 3) reduce the number and/or size of actuators and 4) provide passive gravity compensation. Furthermore, the concept of Controlled Passive actuation was proposed as a possible integral solution.

Currently, the authors are working on the detailed design of a mechanism that realises the proposed approach, future work includes realisation of a prototype and verification the functionality.

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