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A concept for a new Energy Efficient Actuator

In pursuit of the ideal actuator

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***Abstract*—In this paper a novel concept of embedded robotic actuator is presented which has been named the Very Versatile Energy Efficient (V2E2) actuator. This actuator stores energy during any force profile which generates negative work on the load and it does therefore have unprecedented potentials for robotics applications.**

I. Introduction

For mobile robotics and powered prosthetics, the energy consumption is a crucial factor for usability. A reduction of the amount of energy consumed can yield longer operation on a mobile energy source (i.e. battery), or can allow for use of smaller batteries.

There are a number of strategies for reducing energy consumption. One approach is to increase the mechanical efficiency of a device. A second method is to limit waste of energy. Normally, mechanical energy is wasted in a system when doing negative work. Adding a buffer element for storage of mechanical energy, such as a spring, seems a logical solution.

The development of actuators incorporating elastic elements has got a lot of attention in the recent years. One of the first and well known examples is the Series Elastic Actuator (SEA) as developed by MIT [1]. Also a number of compliant actuators with tunable elastic elements are under development, such as the MACCEPA [2] or the 'Jack Spring'™ [3], which allow adjustment of the zero-position of a series elastic element. Another approach is to enable adjustment of the spring constant, by varying the pre-tension of a system using quadratic springs. This approach has been used in for example the VSSEA (Variable Stiffness SEA) [4] and the AMASC [5]. An elaborate overview of the current state of the art is given in [6].

For all mobile robotics applications like humanoids or other legged locomotion, (reduction of) energy consumption is of crucial importance. The previously mentioned examples do have an advantageous compliant behaviour, but in order to change the compliance and obtain different control actions, energy has to be supplied.

An actuator able to intelligently generate reusable energy whenever negative work is done, and able to use this energy whenever necessary would be a great breakthrough in the robotic and active prosthetics world.

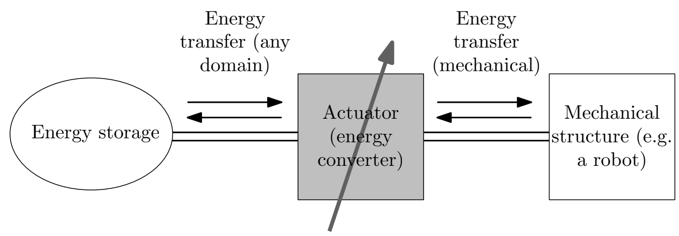

Fig. 1. An ideal actuator is just an energy converter from any domain in which energy is stored to the mechanical domain and vice versa.

In this paper a concept of an actuator is presented which does address the energy efficiently explicitly. This is achieved mechanically with a combination of a Infinite Variable Transmission (IVT) and an elastic element. Extensions are presented to overcome possible realisation restrictions. Experimental and simulation data of an existing walking robot is used for illustrating the proposed concept. The conceptual actuator is dubbed 'V2E2', which stands for Very Versatile Energy Efficient.

A. *Reflections about Actuators*

Usually an actuator is considered as a "signal processor" which translates a command generated by a controller to a physical quantity which is applied on the plant like, a force or torque. More correctly, acting on a physical system, energy is exchanged and in order to describe this properly, it is better to consider an actuator as a controlled device that converts energy from a certain domain in which energy is stored (e.g. electrical, chemical battery or even mechanical storage) to mechanical energy, as schematically shown in Fig. 1. The double lines in the figure represent the energy flow. In an ideal situation, the energy conversion is lossless, no energy is stored in the device, the device has no dynamic effects and the energy flow can be in both directions.

The arrow through the actuator in Fig. 1 represents the fact that the amount of energy converted from one domain to the other can be varied (e.g. by varying the control input signal of the actuator).

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Let us consider for example a normal DC motor, which converts electrical into mechanical energy. The amount of energy converted depends on the load and the input current. An external controller (such as a switching regulator) can modulate the motor's input current, and thereby influence the the amount of converted energy.

In order to allow for a more formal discussion we introduce the concept of power ports. Every block represents an entity which has one or more power ports. The power ports consist in every domain of a coupled pair of variables called effort and flows. In the electric domain these are the voltage v (which is an effort) and current i (which is a flow). In the mechanical domain a force τ (which is an effort) and a velocity ω (which is a flow). In all situations, the product of the effort and the corresponding flow, which are called power conjugate variables, gives the power P which is instantaneously transferred through that port.

In energy converters, we distinguish two types: transformers (the output effort is proportional to the input effort) and gyrators (the output effort is proportional to the input flow). The DC motor is an example of the latter one. Mathematically, an ideal DC motor can be expressed as

$$\begin{bmatrix} \tau \\ v \end{bmatrix} = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \begin{bmatrix} i \\ \omega \end{bmatrix}, \tag{1}$$

where i denotes the input current, v its dual, the input voltage; τ the output torque and ω its dual, the output velocity. In general, the 'gyration ratio' r does not need to be constant (however, it *is* constant in the case of a DC motor), and can sometimes be used to steer the energy flow. It can be observed that $\tau \cdot \omega = v \cdot i$, proving that indeed the energy conversion is lossless and no energy is stored in the actuator.

An ideal actuator would have the following features:

1) Only energy from the energy storage is used if positive work is done on the output port.
2) If negative work is done on the output port, energy flows back into the energy storage. So, there is no loss of energy.
3) If the actuator is controlled in such a way that no energy transfer takes place, the output shaft of the actuator is either perfectly stiff ($\omega = 0$) and can deliver any (static) force or perfectly free-moving and will exert no force to the sytem ($\tau = 0$). The latter situation is called 'fully backdrivable'. In both cases, no mechanical work is done ($P = \tau\omega = 0$), so the energy storage does not need to supply any energy.

An ideal actuator can of course never be made, however, we search for solutions that approach (certain aspects) of it. For the moment, we restrict our search to solutions in which the energy storage domain is the electrical domain (or at least, has a electrical interface). We can think of the energy storage device as being a battery or a (large) capacitor. The most versatile converter from electrical to mechanical energy is the DC motor, which behaves as a non-ideal gyrator.

In many applications like legged locomotion, the actuation is approximately periodic[1]. An example of such a periodic movement is given in figure 4. This data has been taken from the hip joint of our 2D walking robot [9]. The mechanical structure (the leg) has a low and continuously varying velocity in which the direction of movement often changes sign. In this region of operation, a DC motor is an inefficient device: either it needs to run slowly with high torque (in the case of a gearbox with small gear ratio) resulting in a large and heavy motor and bad energy efficiency, or it needs a gearbox with large gear ratio (in case of a better-suited motor) resulting in non-negligible dynamic effects. In the range of operation needed, a DC motor is not a good choice toward an ideal actuator.

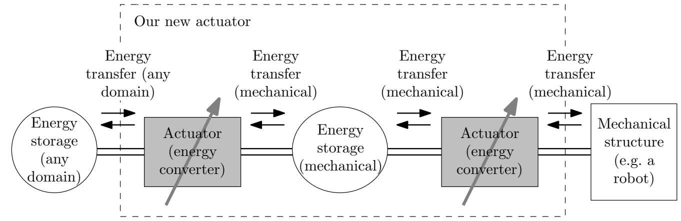

Fig. 2. Our new actuation concept.

We introduce a new actuator concept: an actuator which uses mechanical energy storage as an intermediate step (Fig. 2). As it will be clear from the discussion hereafter, this approach is different from the use of the elastic element in a Series Elastic Actuator.

II. Using IVTs to modulate actuation torques

The general way to approach control of mechanical systems is to use an actuator which generates a mechanical torque which will be applied to an inertial load. The value of this torque should be equal to a specified control signal $u(t)$ and a power amplifier should take care to drain energy from an energy source in order to make the servoing possible during all operations:

$$\tau_d = u(t)$$

Suppose that instead of driving the load directly from the motor, we add to the actuator an Infinitly Variable Transmission (IVT) which is ideal. With ideal we mean that it does not have any losses and it is purely kinematical. The output torque of this system is:

$$\tau_d = n(t)\, u(t) \tag{2}$$

where $n(t)$ is the continuously variable gain and $u(t)$ is the actuator torque. Now we have two ways of varying the output torque: either vary the transmission ratio n or vary the actuator torque u (or both). If n can be both positive and negative, it is possible to achieve positive and negative output torques with a constant (non-zero) u.

[1]If the actuation were exactly periodic, simple solutions exist, e.g. a continuously rotating shaft, actuated by a standard DC motor in its most efficient region of operation, with a mechanical mechanism behind it that converts the rotating motion into the desired periodic motion.

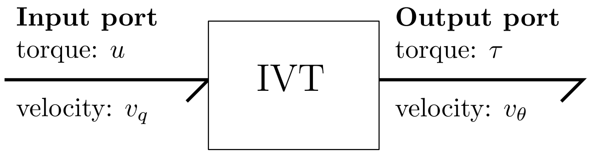

Fig. 3. The ports and port variables of an IVT.

At first, this does not seem to be interesing, but it does become interesting if you realize that the torque u can be provided by any system; it does not necessarily need to be a simple actuator such as a DC motor. One of the possibilities is to attach the IVT to a rotational spring, as explained in the next section.

III. Recovering Negative work

Let us extend the analysis of the previous section to clearly show the energy flows. Firstly, let us introduce the *power port*. A power port, in this specific scalar situation, is a pair of so called dual physical collocated variables which means that the product of these two variables is corresponding to the power flowing between the two subsystems which share those variables.

In the case of the IVT, it has two ports: one on the side where, in the previous section, a constant force source was attached (u, v_q) and one on the side of the load (τ, v_θ) (Fig. 3). The equations of the transmission are therefore:

$$\tau = \quad nu \tag{3}$$

$$v_q = \quad nv_\theta \tag{4}$$

where v_θ indicates the velocity of the axis where τ is applied and v_q the velocity of the other side of the IVT.

A. Adding a Spring

Using again a port model of a spring with state x and elastic constant K, and considering it attached to the port (u, v_q), this would result in the following equations:

$$\dot{x} = \quad v_q \tag{5}$$

$$u = \quad Kx \tag{6}$$

Clearly, by looking at the coupled equations, by controlling in real time n, and supposing that the spring state would never be empty ($x \neq 0$), it would be possible to achieve any desired torque τ_d on the load by a proper control of n, namely:

$$n = \frac{\tau_d}{Kx} \tag{7}$$

This would seem a very complicated way of achieving a desired torque on the load, but by doing so, in case negative work is done on the load ($\tau v_\theta < 0$), this work would not be lost but instead stored in the spring! We could for example make this actuator behave exactly as a physical (non-linear) damper, but the energy, instead of being lost, would be stored in the spring. A problem which still needs to be solved is that the idea would not work in case the string state $x = 0$ or in other words if the spring would be unloaded. This can be easily solved as explained in the next section.

B. Preventing the singular situation $x = 0$

A spring is a nodic element, which means that it actually has two attaching points and that its internal change of state depends on the relative motion of these points. We can therefore attach one side of the spring to the IVT as explained in the previous section, but instead of fixing the other side to a fast body, we could attach it to an electrical drive and control this drive in such a way that the stored energy of the spring would not go under a certain level. In this case, the singular situation $x = 0$ could be avoided. Furthermore, the electrical drive will only have to supply the extra energy which is needed for the load or which should be used to compensate for friction. In case of a periodic motion of the load like many robotics application in leg locomotion, the net to energy exchange between the load and the actuator would be small or equal to zero and such a motor could be dimensioned extremely small. More on the use of this idea for periodic motions can be found in [7].

C. Static load compensation

In many applications in robotics, it is also necessary to keep a certain force constant, but using normal electrical drives this implies a constant loss of energy as heat in the electrical drive. In the presented approach, a constant force will correspond to a certain value n of the IVT and the force will be completely generated by the elastic element and no electrical loss will be involved.

In order to allow this, the motor has to be non-backdrivable. As explained previously, the elastic element will be connected on one side to the IVT and on the other side to an electrical drive which may in some situations be used as generator. On this side, for efficiency purposes, it should be possible to latch this side of the spring and keep it in place without having to generate a force with the electrical drive. This would be necessary in most situations when the spring is working in its nominal region. This latching can be implemented with a small electromechanical clutch on the axis which should be activated only if the angular velocity is zero. An optimal control problem of a hybrid system formulation of this device is currently under study and will be presented in a diferent paper.

D. Electrical Storage

The elastic element which will be used for mechanical energy storage will in general be nonlinear and have a maximum amount of energy it can store. This nonlinear behavior can be taken into account, but physically we would reach a problem if the storage would saturate by getting into a region where the spring simply cannot deform elastically anymore and starts to deform plastically. This problem can be tackled by using the electrical motor, which is used to prevent the complete unloading of the elastic storage, as a generator. While it is most efficient to do energy storage without domain conversion, it would be a waste of energy if the surplus in mechanical storage would simply be dissipated. By releasing the clutch between fixed world and the spring, the motor can be used as a generator, driven by the spring. A reversible motor amplifier has to be used to boost up the generated voltage, and charge a battery.

IV. Realisation

In this section some practical issues will be addressed.

A. The IVT

The most crucial part for the realization of a V2E2 actuator, is an efficient realization of an IVT. The IVT will have a range of continuously variable gains between a positive and a negative value $n \in [n_{min}, n_{max}]$. A proper design will have to be such that changing the gain n in real time would cost very little energy. Furthermore, for the usage presented, the IVT should be connected in such a way that the gain n would correspond to a 0 torque on the load and no motion on the spring side and not the other way around otherwise operation would not be possible.

The conceptual design under study aims for a IVT with a range $n \in [-0.5, 0.5]$. A conventional planetary gear will be necessary to generate output torques in the desired range.

A rotary IVT can be made with the combination of a CVT and a planetary gear by interchanging axes and the fixed world connection in a conventional rotary CVT design. The basic idea is to create a CVT with $m \in [m_{min}, m_{max}]$ creating a speed relation $\omega_1 = m\omega_2$. Furthermore, we can create a gearing system realizing a relation with an additional axis of the form $\alpha\omega_1 = \beta\omega_2 + \omega_3$, which together with the CVT would realize a relation between ω_1 and ω_3 as:

$$\omega_3 = n\omega_2 \;\; n := (\alpha n - \beta).$$

This implies that by choosing proper fixed gear rations α and β, we can achieve a desired range $n \in [n_{min}, n_{max}]$ for negative n_{min} and positive n_{max}:

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} n_{min} & -1 \\ n_{max} & -1 \end{pmatrix}^{-1} \begin{pmatrix} m_{min} \\ m_{max} \end{pmatrix}$$

B. Control

At the moment we are working on the design of an optimal controller for the proposed actuator. The control strategy can be divided into two separate tasks: Recharging the spring and controlling the output torque with the IVT.

The control of the clutch causes the need for a hybrid control solution with two states. The challenge in the design of the controller is to find the optimal point when to switch on the motor. A large part of the gain in energy efficiency of the proposed V2E2 system lies in the fact that the DC motor can be used in its optimal (most efficient) point while recharging the spring. Depending on the energy transfer at the output shaft, the motor can be periodically switched on at its maximum efficiency. As an additional control law, it is necessary to stay away from the state $x = 0$ at all times. The clutch does not necessarily need to be a controlled version. Its primary functioning can also be mechanically solved by using a one-way clutch, in the same way as the winding mechanism of a clock or a wind-up toy.

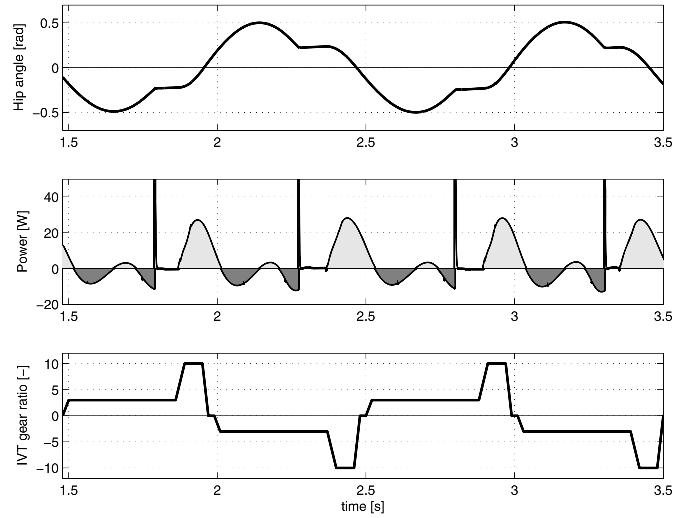

Fig. 4. Simulation data of the 2D powered dynamic walker ‘Dribbel’, showing hip angle, injected power by the hip motor and IVT ratio when using the proposed V2E2 actuator

The IVT ratio is used for control of the output torque. Depending on the desired actuation profile, the ratio can be set at a fixed value, or needs to be changed during a (periodic) motion. Different control schemes apply for different actuation profiles. Consider the control of a walking (humanoid) robot. During a normal walking gait, the hip joint is powered using a periodic profile, requiring a large torque to start the swing-phase of a leg, and braking this motion at the end of the swing phase. For this profile, periodic switching of the IVT will be necessary, from a high gear ratio for the swing-phase torque to a reverse ratio at the end, enabling storage of braking energy in the spring. An example of this movement is shown in figure 4. This data has been taken from a simulation model of our 2D walking robot [9]. The top graph shows the hip angle during a walking motion, the middle graph shows the power that is being injected by a DC motor in the hip (the part that lies below the zero line is the negative work that can be stored in the spring), the third graph shows an impression of the used IVT ratio. The spikes in the power graph are caused by the mechanical locking of the passive knee mechanisms.

During normal walking, the knee joint does not need to be powered [8][9], so a very low ratio ($\approx [\infty : 1]$) can be used, resulting in zero torque as described in the previous section (however, adding a little power can increment the ground-clearance and may improve robustness). When the robot has to do other types of movement with the same joints, such as sitting down or standing up, high gear ratio’s will be required because of the high torques involved. In this case it is not necessary to change the IVT ratio with a very high bandwidth.

V. Consequences for Robotics

The future will learn how efficient the IVT under study will be. Other practical implementations and problems in the realization of the proposed actuator have yet to be tackled, but if this will be successful, the implications for robotics will be

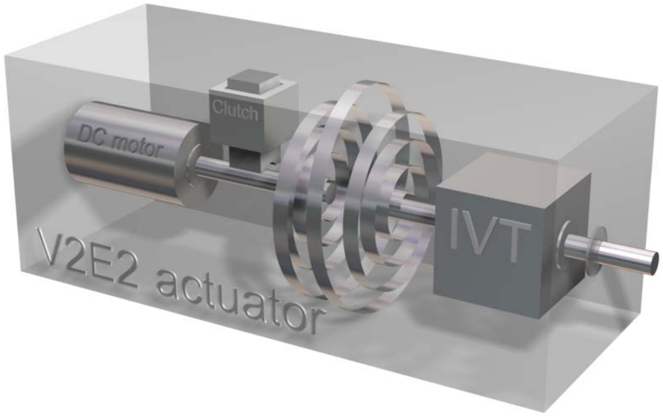

Fig. 5. Conceptual sketch of the V2E2 actuator.

substantial. In legged locomotion people either develop highly geared, fully actuated, robust but not efficient machines or minimally actuated, not robust, but extremely energy efficient machines. A machine which has the robustness of the first group and the energy efficient of the second as yet to come. Such actuators could drastically change this and this was originally the idea which brough the author to conceive V2E2 actuators. We could make a fully V2E2 actuated machine and control it using the most advanced nonlinear control methods without having to worry about the efficiency since the actuators would take care of that. Such devices would therefore bridge the gap which is still existing between advanced but complex and inefficient nonlinear control methods and simple unrobust minimalistic efficient approaches. On the opinion of the authors, this would be a major achievement for robotic locomotion.

VI. Conclusions

A. Proposed system

The concept for a novel embedded V2E2 actuator has been presented which is able to store negative work and create constant forces without conceptually any or small losses of energy. This device will have, in its final form a mechanical and an electrical interface. The mechanical interface will be used as a usual actuator. The electrical interface will have a power connection which will be used bidirectionally to use or charge a battery and a signal control to specify the desired torque on the axis. Internally, with a low power micro-controller, the actuator will take care of steering the device as required, controlling the electric DC motor, the IVT and the clutch. In figure 5 we have sketched the mechanical part of the new actuator.

B. Ongoing work

Some practical problems have still to be solved before the proposed concept will be applicable, first of all the realization of an efficient Infinite Variable Transmission. A lot of progress has been made in this direction and the team of the authors is currently working on a patent. The authors believe that if the practical problems will be overcome, such an actuator could revolutionate the world of many robotic applications especially in legged locomotion and prosthetics.

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References

[1] G. Pratt and M. Williamson. *Series elastic actuators* in Proc. Of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-95), Vol. 1, Pittsburg, PA, July 1995, pp. 399-406

[2] R. Van Ham, B. Vanderborght, M. Van Damme, B. Verrelst, D. Lefeber. *MACCEPA: the Actuator with adaptable compliance for dynamic walking bipeds* CLAWAR 2005: 8th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, 12-15 September 2005 - London, U.K., p 759-766

[3] K. W. Hollander, T. G. Sugar and D. E. Herring. *A Robotic 'Jack Spring' For Ankle Gait Assistance.* Proceedings of IDETC/CIE 2005, ASME 2005 International Design Engineering Technical Conferences 2005, Long Beach, California, USA, September 24-28

[4] I. Thorson, M. Svinin, S. Hosoe, F. Asano and K. Taji: *Design Considerations for a Variable Stiffness Actuator in a Robot that Walks and Runs"* in Proceedings of 2007 JSME Conference on Robotics and Mechatronics, Akita, May, (2007).

[5] J.W. Hurst, J. Chestnutt, and A. Rizzi. *An Actuator with Physically Variable Stiffness for Highly Dynamic Legged Locomotion.* Proceedings of the 2004 International Conference on Robotics and Automation, May, 2004

[6] R. van Ham, T. G. Sugar, B. Vanderborgt, K. W. Hollander and D. Lefeber *State of the Art Actuators with Adaptable Compliance / Variable stiffness for Robotic Applications*, submitted for publication in IEEE transactions on Robotics and Automation, 2008

[7] S.Stramigioli, M. van Dijk *Energy Efficient Limit Cycle Oscillations*, accepted for pubblications at the IFAC World Conference, Seoul, June 6-11 2008.

[8] S. H. Collins, M. Wisse and A. Ruina*A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees* in International Journal of Robotics Research, Vol. 20, No. 2, Pages 607-615, 2001

[9] E.C. Dertien, *Dynamic Walking with Dribbel, Design and Construction of a Passivity-Based Walking Robot* IEEE Robotics and Automation Magazine, pg 118-122, sept 2006