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Compliant Robot Actuation by Feedforward Controlled Emulated Spring Stiffness

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Abstract. Existing legged robots lack energy-efficiency, performance and adaptivity when confronted with situations that animals cope with on a routine basis. Bridging the gap between artificial and natural systems requires not only better sensorimotor and learning capabilities but also a corresponding motion apparatus and intelligent actuators. Current actuators with online adaptable compliance pose high requirements on software control algorithms and sensor systems. We present a novel feedforward trajectory shaping technique that allows for a virtual stiffness change of a deployed series elastic actuator with low energy requirements. The performance limits of the approach are assessed by comparing to an active and a passive compliant methodology in simulation. For this purpose we use a 2-degrees-of-freedom arm with and without periodic load representing a 2-segmented leg with and without ground contact. The simulation results indicate that the approach is well suited for the use in legged robots.

Keywords: locomotion, gait transition, feedforward control, spring stiffness, compliance, series elastic actuation

1 Background

A key prerequisite of versatile and energy-efficient legged robots that move in a-priori unknown environments are proper actuation modules. Recent research has focused more and more on actuators with adaptable compliance that can change joint stiffness in order to adjust the overall leg properties with respect to robustness, energy efficiency and speed of motion.

One way to vary the compliance of an actuator is by software, i.e. impedance control of a stiff actuator. Based on the measurement of the external force or torque, the controller of the stiff actuator can mimic the behavior of a spring-damper system. This type of compliant actuators requires actuators, sensors, and controllers that are all fast enough for the target application in order to permit virtual compliance adjustment during operation. The programming of the characteristic of an imitated spring and its online adjustment is also known as active compliance [8]. The disadvantage of such actuators is the continuous energy dissipation since no energy can be stored in the actuation system. Furthermore, fast shocks can not be absorbed because of limited bandwidth of the controller.

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The use of springs in legged locomotion is generally accepted as important and has been promoted very early [4]. Elasticity of legs, partially storing and releasing energy during contact with the ground, allows to achieve stable, rapid and energy-efficient locomotion. In fact, mechanical elasticity is a prerequisite for ballistic human- and animal-like movements. Passive compliance actuators contain at the minimum an elastic element. Their designs are divided into four groups: (1) equilibrium-controlled stiffness, (2) antagonistic-controlled stiffness, (3) structure-controlled stiffness, and (4) mechanically controlled stiffness [1]. A famous example of the first group is the original series elastic actuator (SEA) [5], a (stiff) rotary joint actuator in series with a spring. The compliance of the actuator is limited by the spring constant and is therefore not adjustable during operation. Easy force control is enabled by measuring the spring elongation and returning in a feedback loop.

This short foray into current actuation mechanisms and techniques reveals prevalent difficulties. Actuators require complex software control algorithms and sophisticated sensor systems in order to behave adaptable and compliant in contact with unknown environments. An actuation unit that can reach the performance of the biological muscle and its neuro-mechanical control system is missing. On the other hand, actuation mechanics and principles strongly depend on the application.

In this paper we present a new, basic but effective technique enabling variable compliance. We combine energy storage and adaptable compliance by using elastic elements to store energy and applying a method to change the compliance during operation. The actuation mechanism and technique are explained in Section 2. In Section 3 the proposed methodology is compared to purely active and passive compliant actuation using a 2-degrees-of-freedom (DOF) arm in a simulation study. The paper concludes with a discussion on the advantages and disadvantages of the presented actuation techniques with respect to legged locomotion.

2 Emulated Spring Stiffness

2.1 Actuation Mechanism

Joints are actuated by bionic drives consisting of a DC motor that is elastically coupled to the joint with antagonistic, elastic pulleys with progressive angle-torque characteristics, as illustrated in Fig. 1. This actuation module has been tested extensively in a real manipulator, the *BioRob* arm [3], and simulated four-legged robot [6] and falls into the category of SEAs. Compared to the original SEA [5], however, it allows the actuation of distal joints by means of the antagonistic pulleys resulting in low mass and inertia of the joint [9]. It also enables pretension of a joint. For the remaining of the paper and our experiments, however, we make use of rotary SEAs without encoders at the joints.

2.2 Technique

The deployed spring in each actuator has a predefined mechanical constant stiffness, therefore the physical compliance can not be adjusted during operation. But a dynamic adjustment of the equilibrium position of the spring, i.e. a different motor triggering,

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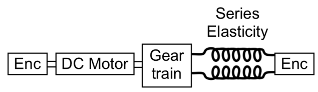

Fig. 1. Schematic of the actuation module, used in the *BioRob* arm [3] and a four-legged robot [6].

leads to a dynamic change in joint trajectory resulting in a different "virtual stiffness" of the actuator. We assume that the system is fed with a sine signal as reference input, similar to a pendulum movement between two angles, as shown in Fig. 2. Furthermore we assume a linear characteristic curve for the spring deployed in the actuator. We then use the following equations to correct the input signal such that the response of the system is adapted to the desired stiffness:

$$\rho_1 = \frac{\phi_1}{2} + \frac{\phi_2}{2} + \frac{\mu \cdot |\phi_1 - \phi_2|}{2 \cdot k} + o\,, \tag{1}$$

$$\rho_2 = \frac{\phi_1}{2} + \frac{\phi_2}{2} - \frac{\mu \cdot |\phi_1 - \phi_2|}{2 \cdot k} + o\,, \tag{2}$$

where k represents the mechanical stiffness of the deployed spring and μ the desired virtual spring stiffness. The variables ϕ_1 and ϕ_2 denote the two input angles between which the movements are oscillating whereas ρ_1 and ρ_2 stand for the novel, corrected angles due to the adjusted spring stiffness.

In reality, though, the linear spring does not represent the actual spring characteristic. Note that the system is not feedback-controlled, which also means, that dynamic movements of other joints affecting the positions of coupled joints are not taken into consideration by the controller. Consequently, a system that is feedforward controlled with these equations will produce deviations. Therefore, a manually tuned correction offset o is introduced in the Eqs. 1 and 2 to reduce the deviations.

The corrected sine trajectory with the upper and lower limits ρ_1 and ρ_2 based on the desired virtual spring stiffness parameter μ equals the motor position trajectory which generates spring torques τ_k and damping torques τ_d on the spring of the actuation module. The actuated revolute joint responds solely by mechanical feedback. For better clarification, this above described feedforward controlled emulated spring stiffness technique is also illustrated in Fig. 3.

3 Comparison of Different Techniques For Adaptable Compliance

Both concepts of active compliance and passive compliance are integrated in the proposed technique. Consequently, in order to assess the performance limits of our approach, we compared it to active compliance as realized in the DLR lightweight arm Justin [8] and passive compliance as realized with the mechanically controlled stiffness actuator Maccepa [2]. Since active compliance requires exact knowledge of the model, we modeled a basic 2-DOF arm that is used in the following for all comparisons. In order to apply active compliance, we also developed the inverse dynamics model of the 2-DOF arm. For replicability of the simulation results we listed the exact model

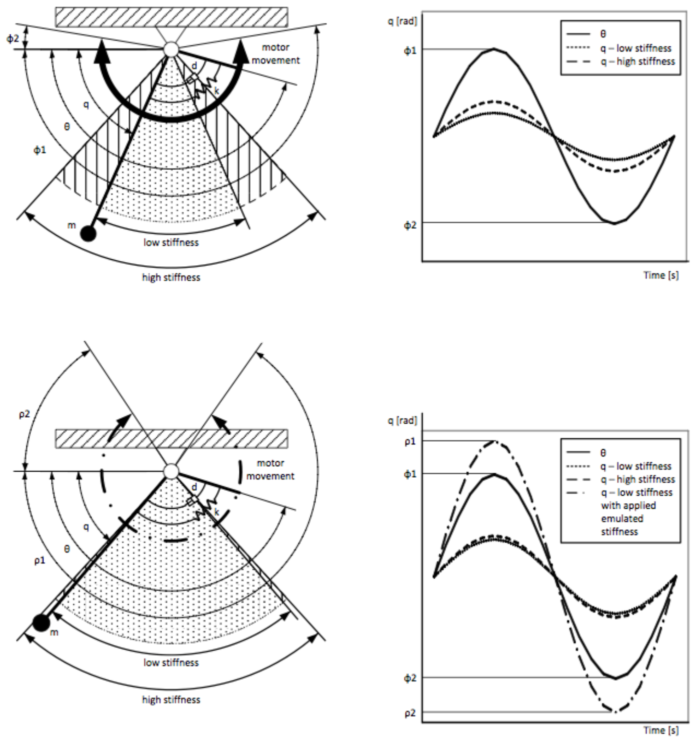

Fig. 2. Upper picture illustrates the resulting trajectories of a 1-DOF pendulum with a rotary SEA with low and high mechanical constant stiffness. A pendulum oscillates between the angles ϕ_1 and ϕ_2. Stiffening the spring in the actuator leads to an extension of the movements, a higher amplitude. ln the below picture the emulated spring stiffness technique is applied. As shown, even the system with the low mechanical stiffness can extend its movements by means of the emulated spring stiffness technique to the intervall $[\rho_1, \rho_2]$.

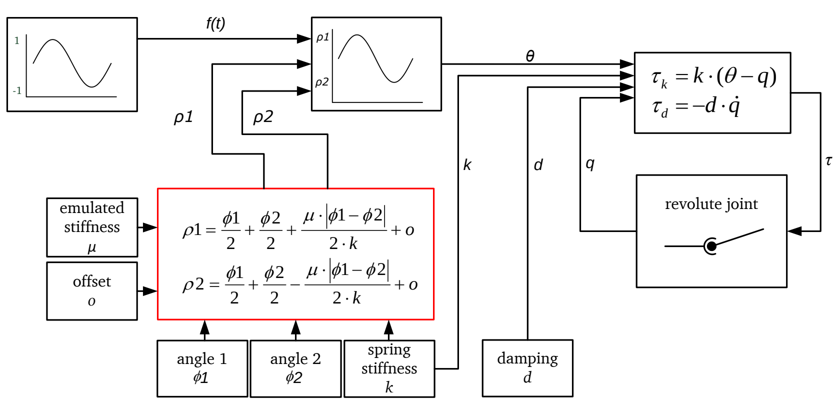

Fig. 3. Schematic of the feedforward controlled emulated spring stiffness technique.

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Table 1. Model Parameters of the 2-DOF arm.

link length	L_1	$0.3\,\mathrm{m}$
	L_2	$0.3\,\mathrm{m}$
link mass	m_1	$0.2\,\mathrm{kg}$
	m_2	$0.2\,\mathrm{kg}$
link radius	r_1	$0.02\,\mathrm{m}$
	r_2	$0.02\,\mathrm{m}$
link inertia	I_L	$E \cdot \left(4 \cdot 10^{-5},\, 1.5 \cdot 10^{-3},\, 1.5 \cdot 10^{-3}\right)^{\top}$
motor inertia	I_M	$0.33\,\frac{\mathrm{kg}}{\mathrm{m}^2}$
gear inertia	I_G	$0.07\,\frac{\mathrm{kg}}{\mathrm{m}^2}$

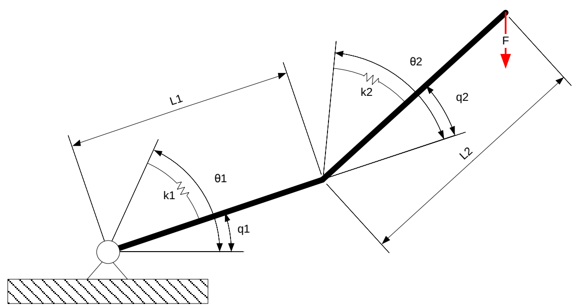

Fig. 4. Both joints of the 2-DOF arm are actuated by rotary SEAs. The variables θ_1 and θ_2 represent the motor positions while q_1 and q_2 stand for the joint positions. k_1 and k_2 denote the predefined mechanical spring stiffness of the SEAs.

parameters in Table 1. The 2-DOF arm, as depicted in Fig. 4, can also be considered as a 2-segmented leg. Ground contact is simulated by an additional periodical load at the end of the arm.

The experiments are set up in the numerical computing environment Matlab. We performed different simulation runs, varying the “step frequency” of the 2-segmented leg and simulating an additional periodical ground. Due to the limited number of pages we will only focus on important aspects found in the simulation runs.

3.1 Experiment 1 with Step Frequency $f = 0.5\,\mathrm{Hz}$

The data input for this experiment is illustrated in the two uppermost plots in Fig. 5. Both joints of the 2-DOF arm are fed with the same sine wave with the frequency $f = 0.5\,\mathrm{Hz}$. The mechanical and emulated stiffness line overlap, i.e. emulated stiffness changes as the mechanical stiffness does. The stiffness is linearly changed from $5\,\frac{\mathrm{Nm}}{\mathrm{rad}}$ to $14\,\frac{\mathrm{Nm}}{\mathrm{rad}}$ during the simulation time of $9\,\mathrm{s}$. Furthermore, the correction offset and the occurrence of ground contact, signalized by load, are displayed. This first run was conducted without ground contact.

Note that the deviations, i.e. squared errors, shown in the figures are all based on the so-called “ideal model”. The ideal model represents a system with “online adapt-

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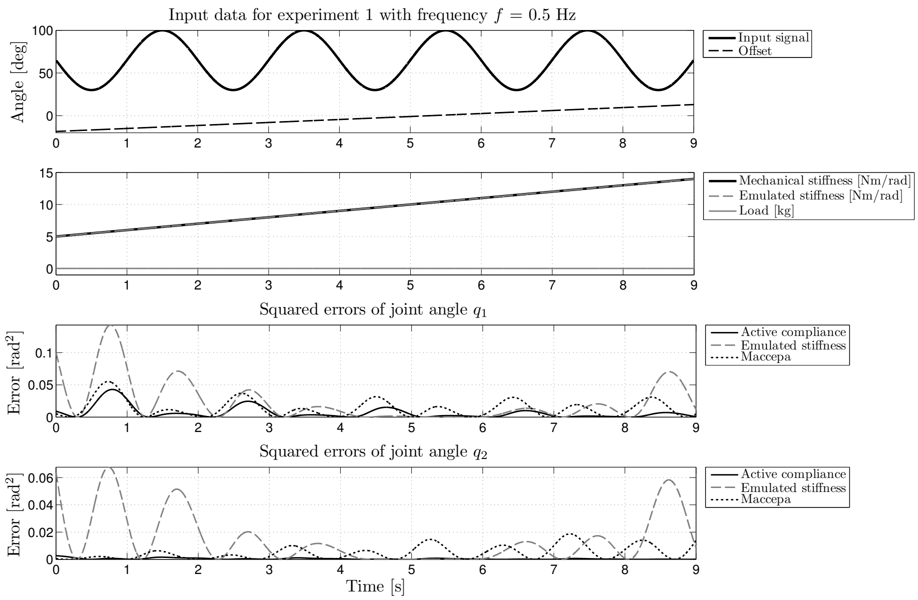

Fig. 5. Experiment 1: Sine wave as reference input for both joints with given emulated and mechanical spring stiffness with a step frequency of 0.5 Hz. The experiment is performed without ground contact.

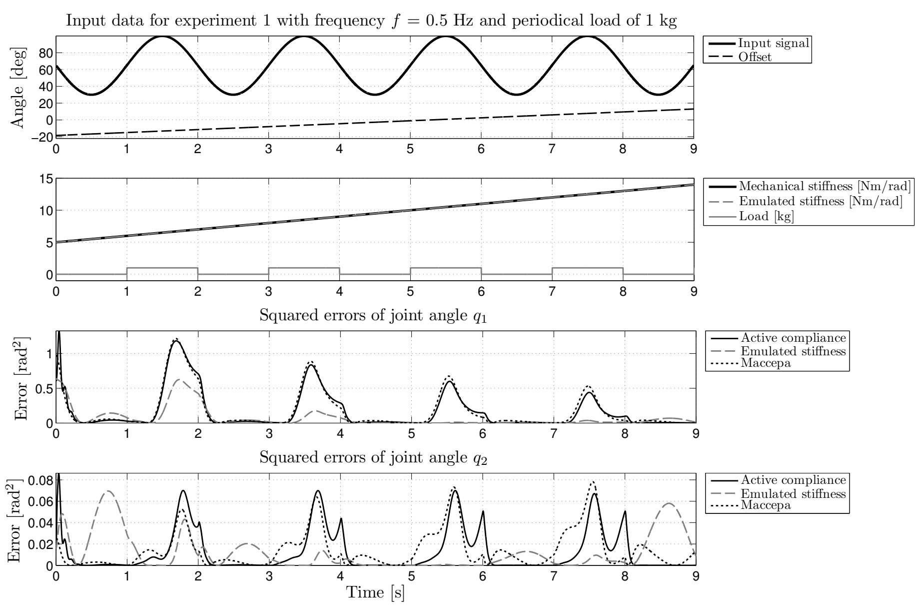

Fig. 6. Experiment 1, i.e. sine wave as reference input for both joints with given emulated and mechanical spring stiffness with a step frequency of 0.5 Hz, is repeated additionally with ground contact which is achieved by a periodical load of 1 kg.

able spring stiffness" without any prerequisites such as special hardware or computing power. We assume that in simulation we can change the mechanical spring stiffness at any specific time without consuming energy. A real mechanical spring stiffness cannot be changed sufficiently quickly. Thus the ideal system represents only an imaginary system.

The squared errors of the techniques "active compliance", "emulated stiffness", and "Maccepa" are separately illustrated for each joint in the third and fourth plot of Fig. 5. It can be recognized that the deviations of all techniques amount to the approximately same value after transition into steady state, less than 10°. In order to motivate legged locomotion with this kind of actuation, the same run was also performed with simulated ground contact, shown in Fig. 6. Compared to the first experiment, the squared errors increase for both joints during simulated ground contact with all techniques. Considering that positioning accuracy in dynamic locomotion does not or should not play an important role, however, we can adhere that the emulated spring stiffness technique copes well with the additional periodical loads.

3.2 Experiment 2 with Step Frequency $f = 3\,\mathrm{Hz}$

In this experiment we increased the step frequency by $f = 2.5\,\mathrm{Hz}$. We could observe that the squared errors of the active compliant and Maccepa actuated system increase while those of the emulated spring stiffness technique stay stable. Both joints of the arm approximate the desired trajectories with approximately the same precision as in Experiment 1.

3.3 Experiment 3 with Step Frequency $f = 5\,\mathrm{Hz}$

In our last experiment we changed the stiffness linearly from $4\,\frac{\mathrm{Nm}}{\mathrm{rad}}$ to $34\,\frac{\mathrm{Nm}}{\mathrm{rad}}$ during the simulation time of $30\,\mathrm{s}$. Furthermore the step frequency was increased to $5\,\mathrm{Hz}$. The runs shown here are performed without ground contact. The results obtained with the emulated spring stiffness technique indicate slight improvement despite higher frequency (see Fig. 7). Active compliance and Maccepa actuators, however, yield deviations that seem to grow synchronously with the frequency.

In order to probe the causes of the large deviations with active compliance and Maccepa actuators we examined the actual trajectories more in details. In Fig. 8 we compare the sensed responses, i.e. measured trajectories, q_1 and q_2 obtained by an ideal system with online adaptable spring stiffness with the responses obtained by Maccepa actuators and the active compliant system. As the uppermost plot in Fig. 8 indicates, the deviations of the actual trajectory q_1 with Maccepa actuation are large whereas the deviations of the actual trajectory q_2 about approximately 7° are still bearable for applications in legged locomotion. Taking a look at the actual trajectories obtained with the active compliant system, we note surprisingly that the deviations are in fact smaller than assumed solely by the squared errors. The measured trajectories approximate the ideal given trajectories both in the shape and amplitude quite well. Consequently, the large squared errors seen in Fig. 7 are not due to the small deviations of the amplitudes but rather due to the phase shifts.

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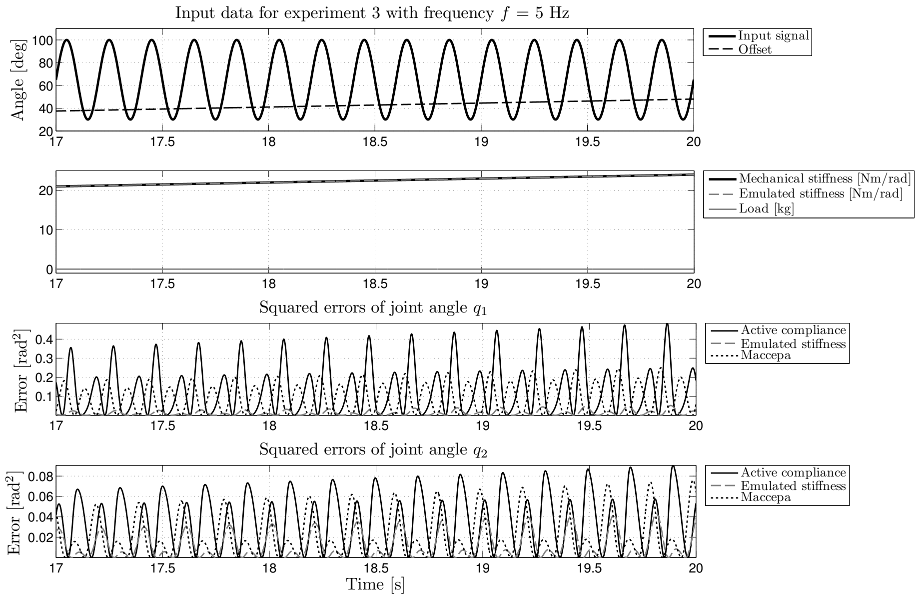

Fig. 7. Experiment 3: Similar setup as in Experiment 1, sine wave as reference input for both joints with given emulated and mechanical spring stiffness with an increased frequency of 5 Hz without ground contact.

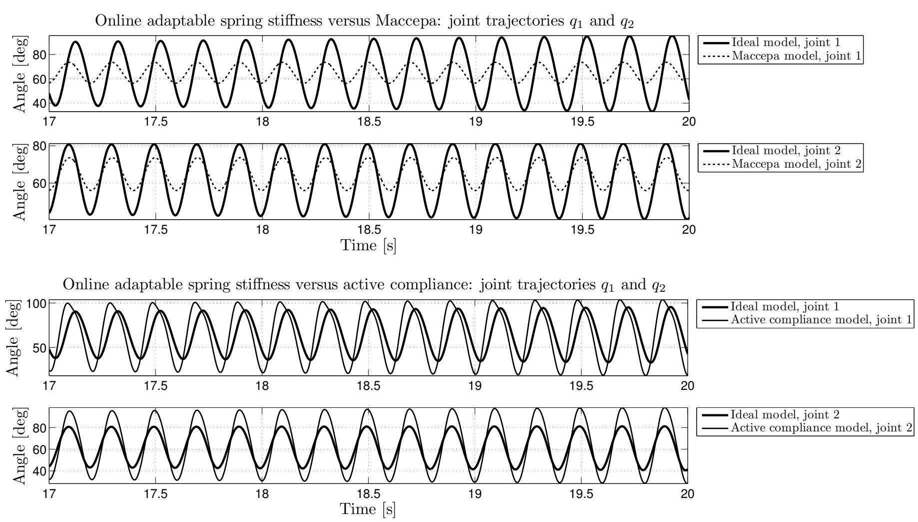

Fig. 8. Actual trajectories respectively measured responses obtained by the 2-DOF arm with online adaptable spring stiffness are compared to the responses obtained by Maccepa actuation for joints 1 and 2 in the uppermost plot. In the lower plot the responses of the ideal system with online adaptable spring stiffness are compared to the responses of the active compliant system.

In order to assess the performance of the emulated spring stiffness technique, we also compared both the desired reference inputs and measured responses obtained with the emulated spring stiffness technique with the inputs and responses obtained by the ideal system with online adaptable spring stiffness. Fig. 9 displays the input and response trajectories q_1. Neglecting the insignificantly small time delay between the actual trajectory of the ideal model and that of the emulated spring stiffness technique, we can note that the sole amplitudes of both actuation systems are almost identical. The model controlled by the emulated spring stiffness technique behaves almost exactly like a model with a mechanical spring stiffness that can change continuously online during operation.

When discussing different possibilities of actuation, not only the deviations play an enormous role but also the required motor torques and velocities. Therefore, we also examined the torques and velocities required for the desired trajectories of this experiment. The velocities are not illustrated here, but they have also been examined. The velocities that are needed for the displayed motor torques can be generated by the same motor-gear combinations that generate the torques. As expected, the motor torques required for an active compliant system or Maccepa actuation are at least twice as high as for the ideal model with online-tunable spring stiffness (cf. Fig. 10). Interestingly the emulated spring stiffness technique requires even less torques than the ideal system with online adaptable spring stiffness.

4 Discussion

The purpose of the previous section was the evaluation of the performance and limits of the proposed technique of emulated spring stiffness in terms of deviations and motor specifications when comparing to two other techniques. Both techniques, the torque-controlled approach and the mechanically stiffness control with Maccepa actuators, are well known and often used methodologies. The large deviations observed in the figures are due to particular application dependent details, modeling inaccuracies and the used error measure.

Provided that the exact dynamic equations of the model are known and the inverse dynamics model is correctly determined, active compliance allows the accurate realization of a desired trajectory with any spring constant and damping value. Interestingly, this method requires neither elastic drives and elements nor any further additional hardware. Thus, it does not result in further weight and additional masses and inertias of the actuation module. The downside, however, is the computational complexity that is even more of a disadvantage when fast periodical motions of a more complex system than a 2-DOF arm are to be controlled. Furthermore, virtual compliance subsists on feedback, and therefore sufficiently fast sensors are essential. Due to the critical sensory flow, known in robotic applications, this technique may decrease in performance for fast motions. The noticed deviations of the active compliant system are owed to the error measure which is based on both the phase shifts and the deviations of the amplitudes. A different measure based only on the deviations of the amplitudes would yield smaller errors than depicted in the above figures.

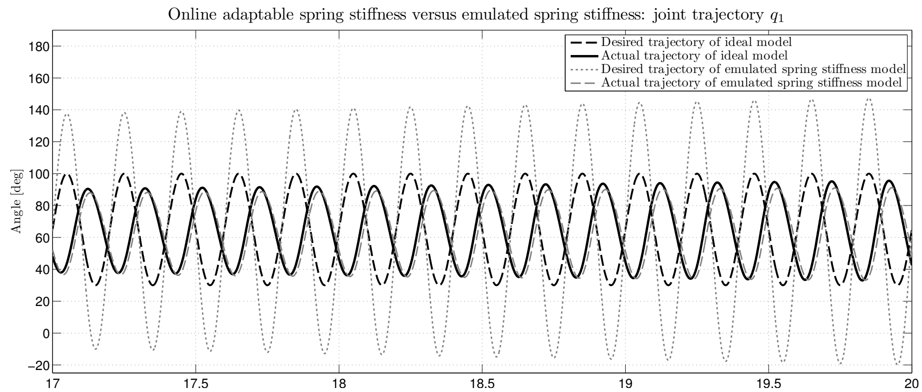

Fig. 9. Desired and actual trajectories obtained by the ideal system with online adaptable spring stiffness for joint q_1 versus the input and response trajectories obtained by the emulated spring stiffness technique.

As for Maccepa actuator, it remains to say that on-the-fly adjustment of the effective physical stiffness of a system by a small light motor is crucial and advantageous. It also has been used in the bipedal robot Veronica. However, the additional mass and inertia of the special joint construction play an important role in the energy increase [2]. Furthermore, due to the complex actuation mechanism the modeling of the actuator is quite challenging. For instance, the lever arm changes depending on the current configuration. These and other details that we were not able to consider in the simulation model without undertaking tremendous efforts lead to the noticed deviations.

The comparisons were designed to better assess the performance limits of the proposed technique. Results at this stage of investigations indicate that the emulated spring stiffness technique has the potential to be used in legged robots. Compared to other compliant actuators the mechanics of the proposed actuation can be considered as rather simple. It basically represents an extended SEA. Additionally, the implemented control strategy given by Eqs. (1) and (2) managed to approximate the given trajectories in the experiments described in Section 3 very well, requiring beforehand a manually tuned correction offset to reduce occurring deviations.

As pure feedforward control strategy it does not need any sensory system. In general, no special hardware, most importantly no additional motor that would in turn result in additional weight, is required. The method does not require any prior knowledge about the model and can be applied to any joint. The technique turns out to represent a good combination of active and passive compliant actuation. Further investigations need to be carried out to ensure its advantages for different, also non-periodical motions. At the current development stage, if a position is held for a certain time, deviations to the desired position will occur. As Eqs. (1) and (2) do not approximate the real characteristic curve of the deployed spring, some parameters such as the offset o must be adapted to the specific operation. Therefore, this type of actuator and controller is even more advantageous if a prior analysis is performed to choose and determine the necessary force-elongation characteristic of the spring as well as the resulting compli-

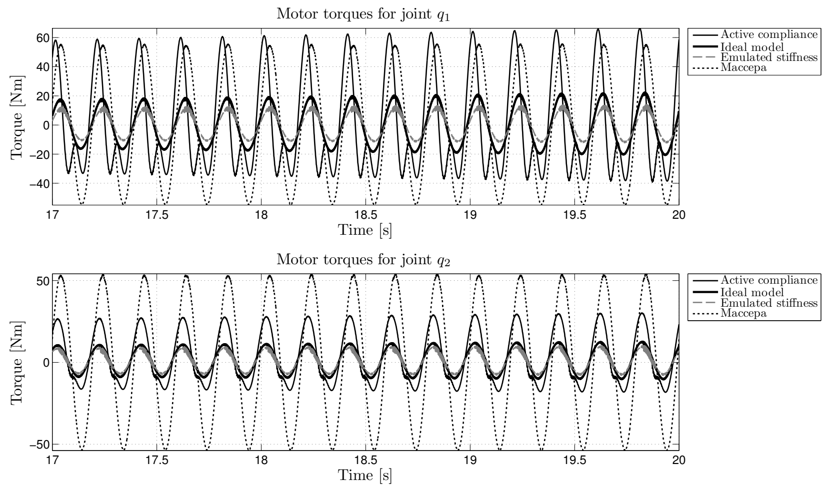

Fig. 10. Motor torques required for the desired trajectories q_1 and q_2 generated by the ideal system with online adaptable spring stiffness, active compliant system, Maccepa actuators and emulated spring stiffness technique.

ance characteristic of the overall system. We are currently investigating a method to integrate a such prior analysis into the design of the proposed actuation module beforehand. Furthermore, the actuation principle can be enhanced by an intelligent coupling of feedforward and feedback control.

Finally, this kind of compliant actuation is essential in order to realize multiple modes of locomotion and locomotion on different terrains with varying ground stiffness in changing, unstructured environments. As this technique allows to change the joint stiffness online, it is possible to change the overall leg stiffness and therefore to change online the gait of a legged robot. An adjustment of leg stiffness leads to a different ground contact duration per step which in turn results in a different gait. This can be achieved solely by changing the emulated spring stiffness parameter μ (cf. Eqs. (1) and (2)). We have integrated this type of actuator and controller in a four-legged robot in simulation and experienced performance gains in the sense of multimodal locomotion: a real gait transition from walking into trotting was initiated by the emulated spring stiffness technique. For further details regarding the four-legged robot and online gait transitions we refer to [7].

5 Conclusion

To the end of developing biologically inspired legged robots that are capable of versatile, robust and efficient locomotion compliant actuation modules are essential. In this paper a basic but effective technique for the realization of adaptable compliance has been proposed and investigated. The underlying mechanical structure of the proposed actuation principle is a SEA containing two elastic elements. The implemented feedforward controller emulates the effect of a real change of the mechanical spring stiffness,

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requiring however a manually tuned correction offset for the small occurring deviations. The proposed technique was compared to an active compliant torque-controlled approach and a mechanically controlled stiffness technique using a 2-DOF arm. The results demonstrated that the proposed methodology can be applied to fast periodical motions with and without ground contact for legged locomotion. A system that is feed-forward controlled with the presented actuation module behaves almost like a virtual ideal system with online adaptable mechanical spring stiffness at any time, however coming at the price of small deviations. The developed technique requires neither prior knowledge of the model nor any hardware and computing power. Adaptable spring stiffness is, of course, necessary if different gaits shall be demonstrated. A legged robot using the proposed actuation module, as shown in simulation so far, is capable of different gaits, by changing only the emulated spring stiffness parameter. Investigations on a real robot model are necessary to assess the performance limits of the presented technique for real applications in the future.

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