Preprint of the paper which appeared in:
Proc. 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, pp. 3771-3778, 2015.

A Systematic Approach to the Design of Embodiment with Application to Bio-Inspired Compliant Legged Robots

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***Abstract*— Bio-inspired legged robots with compliant actuation can potentially achieve motion properties in real world scenarios which are superior to conventionally actuated robots. In this paper, a methodology is presented to systematically design and tailor passive and active control elements for elastically actuated robots. It is based on a formal specification of requirements derived from the main design principles for embodied agents as proposed by Pfeifer et al. which are transfered to dynamic model based multi objective optimization problems. The proposed approach is demonstrated and applied for the design of a biomechanically inspired, musculoskeletal bipedal robot to achieve walking and human-like jogging.**

I. Introduction

Bipedal robots have achieved remarkable results in locomotion. Robots as, e.g., the two-legged humanoids Honda Asimo [16], BioBiped [15] or LOLA [6] feature remarkable dynamic locomotion capabilities. When considering mechanical design and actuation approaches for legged robots, two typical concepts can be seen: A robot design based on rigid kinematic chains with stiff actuation, and robots designed with highly elastic actuation often motivated by human and animal locomotion. The elastic actuation concept usually provides, that an elastic element is installed in series between the actuator and the respective link. When targeting the application in new scenarios, as for example unstructured real world environments, robots which follow the design approach with elastic actuation have three potential major advantages over stiff robots:

- Physical interactions are less dangerous for robot hardware components. Peak forces, that occur in contact situations for example, are filtered by the applied springs. In doing so the stress on gears and actuators is reduced.
- Energy from impacts can partly be stored as potential energy and re-used to amplify the lift-off motion. This is especially relevant for robots that are autonomous with respect to their energy supply.
- The robustness with respect to variations in time and position of impact is increased. Since physical elements do not require reaction time, an instantaneous reaction to disturbances is possible.

A robot properly constructed with highly elastic joint actuation is therefore applicable in unstructured environments more efficiently then its rigid equivalent. However, this design approach also has some drawbacks. On the one hand it is more difficult to construct a robot with highly elastic actuation. The implementation of elements with complex dynamic properties increases the complexity of the robot's kinematic and dynamic structure and behavior. To achieve an overall increase of the robot's efficiency, a proper layout of the structure is therefore required. On the other hand it bears a challenge to operate a robot with highly elastic actuation. The increase in complexity of the robot's hardware typically results in a highly non-linear dynamic system. Common linear control approaches can only be applied with work-around solutions, as for example cascade control.

A possible approach to address the challenges in development and setup of these highly elastic robots is the consideration of the robot hardware as part of the control. In addition to the established (active) control, which is based on sensors and actuators, the (passive) hardware influences must be adapted in order to achieve the desired system behavior. These passive hardware influences are considered as passive control elements within this approach. Together with the idea, that not only the robot determines its behavior, but the robot together with the environment is deployed in, this is also known as concept of embodiment.

Although the concept of embodiment is discussed within multiple publications [12], [11], [13], [4], a systematic approach to make it available for the development and construction of legged robots is missing. This paper aims towards systematically analyzing and formalizing the main design principles for embodied agents by Pfeifer et al. [11] for the application in a development process for legged robots. For this purpose, these are mapped to a hardware development approach, which is based on a multi-experiment and multi-objective optimization of a multi-body dynamics model of robot and environmental interaction.

This paper concludes with the application of the proposed design of embodiment approach to the design and setup of the two-legged musculoskeletal BioBiped2 robot.

II. Related Work

Several authors have investigated dynamic model based optimization of passive body dynamics and control properties for bipedal robots like [18]. However, to the best knowledge of the authors, none of them has yet aimed for a systematic coverage of all eight main design principles for embodied agents by Pfeifer et al. as described, e.g., in [11]. Therefore a number of important properties, like multiple objectives and multiple experiments, have not been considered. Also these investigations are usually only performed for simulation models but not carried over to real robot models.

For the systematic development of two-legged robots usually established approaches for general mechatronic sys-

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tems and robots are applied. A specific approach to design the hardware of mechatronic systems is described in guideline VDI 2206: design methodology for mechatronic systems [17]. In [2], [6] Buschmann et al. follow this iterative approach to develop the legged robot LOLA. Although several motion types can be considered in this approach to guarantee the required versatility by the application of different load cases, possible interdependencies are not regarded. Since only specific load scenarios are considered, but not the effects of physical interactions during operation, the design of an embodied agent is therefore not easily possible with this conventional approach.

Eberhard and Bestle [3] developed a dynamic model based optimization approach for general multi-body systems considering multiple objectives. The approach presented in this paper aims at a related approach for integrated modeling, simulation and optimization of embodied agents.

Approaches, which systematically apply the main design principles for embodied agents [10], [11] to a robot development process are missing to date. There are several considerations though, which discuss the embodiment concept in context of robotics, like the work of Pfeifer, Iida et al. [10], on which the approach presented in this paper is based upon. A strongly related approach has been develoepd in the mobiligence project [1], [9]. In this project implicit control commands, which result from interactions with the environment are analyzed and complex control laws are derived. However, not all design principles for embodied agents have been considered (like multi-objective and multi-experiment for versatility) and its application to complex robot designs is still not completed.

The approach presented in this paper is a new methodology for the systematic design and setup of passive and active control parameters of legged robots with bio-inspired highly compliant joint actuation. By considering the interdependencies within involved components the benefits of highly elastic actuation can be utilized. This is achieved by systematically transfering the main design principles for embodied agents to a dynamic model based multi-objective and multi-experiment optimization problem.

III. PRINCIPLES OF EMBODIMENT

In [11] a detailed description of embodied agents is presented in eight main design principles. The proposed design of embodiment approach utilizes these principles to design and setup a legged mobile robot by formalizing these as requirements for a complex model-based optimization approach. Due to space limitations, in the following the two most relevant principles are discussed and evaluated in detail. Also a missing ninth design principle (efficient versatility) is introduced.

A. The three constituents principle

Designing an intelligent agent involves the following constituents: (1) definition of the ecological niche, (2) definition of the desired behaviors and tasks and (3) design of the agent [11, p. 100, Sect. 4.3].

According to this design principle, the development process of an agent involves the consideration of additional factors besides the actual agent's hardware. Important additional components that influence the agent are its ecological niche and the definition of tasks and behaviors.

The three constituents principle states to consider the design of the actual robot hardware together with its physical constraints and the desired motion goals. All three constituents must be considered from the beginning of the robot development process.

The applied optimization approach must therefore be able to consider and utilize all relevant constraints, which are defined by the three constituents.

B. The complete agent principle

The complete agent principle states that when designing agents we must think about the complete agent behaving in the real world [11, p. 104, Sect. 4.4].

This design principle emphasizes the importance of a comprehensive consideration of the agent and the according interactions with the environment in agent design.

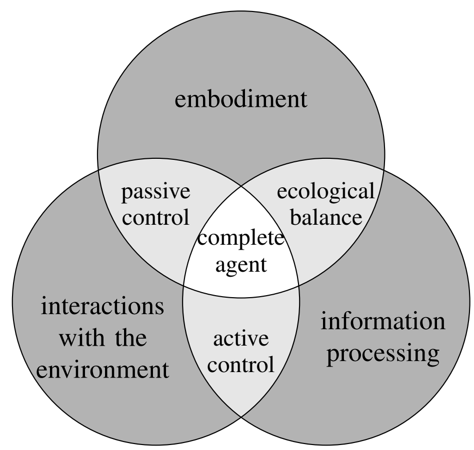


Fig. 1: According to the second principle, the complete agent includes the embodiment, required information processing and the interactions with the environment.

According to Pfeifer and Bongard, the term *complete agent* covers all components defining the agent and its behavior:

- The embodiment, as the physical representation of the robot, includes all hardware parts of the robot. This also covers the dynamical properties of sensors and actuators, like masses or the generated forces.
- The information processing includes all signals without physical representation. Information processing in a robotic system are the sensor signals, feed forward signals or other signals that occur during computations. These signals have to be processed and applied to an actuator to take appropriate effects on the embodiment.
- The interaction with the environment has an effect on the embodiment and on the sensor signals. A consideration of these interactions is therefore crucial for the layout of the agent.

Figure 1 shows the specified three modules of the complete agent principle together with their connections from control perspective.

- The interactions between the embodiment and the environment are manifold. To direct and adapt the behavior of the agent regarding the desired goals with the embodiment only, passive control approaches can be applied. Passive control is applied wherever hardware exists. Just by being existent in the real world, the behavior of an object is constrained. The layout and adaption of passive control parameters, which positively influence the behavior of a legged mobile robot, is part of the design of embodiment approach.
- The interactions between the environment and the information processing must happen via active sensor and motor components. Therefore depending on the number of sensors and actuators, only a small number of interactions can occur. Due to the abstract nature of the information processing, a fast and simple adaption of the reactions to the sensed data is possible, allowing to react to even complex events with a suitable motor actuation.
- Embodiment and information processing also interact during an agent's operation. It is therefore necessary to carefully arrange sensors and actuators within the embodiment, based on the interactions with the environment in the considered task. This important issue is subject to the agent design principle five: ecological balance [11]. Due to space constraints this principle is not discussed within this paper in detail however.

The principle of the complete agent implies to simultaneously consider active control parameters, passive control parameters, and the arrangement and dimensioning of active control elements in the development of embodied agents.

The comprehensive setup of the passive and active control parameters is therefore a central part of the design of embodiment process.

C. Efficient versatility

The new principle of efficient versatility is not included in the original eight agent design principles by Bongard and Pfeifer. It is rather added to address the relevant issue of versatility in legged locomotion.

Typically passive control elements have constant control properties. These control properties can be dependent on a current configuration like position, velocity or force, but cannot be varied independently, like elements that are actively controlled.

The requirements to the embodiment and therefore to the passive control structures are defined by the ecological niche and the respective tasks of the agent. This complex set of requirements results in different, possibly opposing demands to the constant passive control elements.

Passive dynamics walkers as for example in [7] are only capable to perform one task in one specific ecological niche. Not applying any active control reduces the versatility in this example.

An important target of the design of embodiment approach is the adaption of passive interactions, such that passive control actions are preferred over active control, while achieving the desired performance and versatility of the agent.

In different scenarios, the agent is exposed to different requirements with respect to the interactions with the environment. An approach pursued by the design of embodiment is to find optimal configurations for the active and passive control elements for each scenario defined by the ecological niche and the tasks. By considering the agent in the simulation of multiple complex motion tasks, the versatility is considered explicitly.

The results of the simulation must be evaluated carefully to find the optimal design of the embodiment. The desired optimal embodiment has the ability to utilize physical elements to generate or direct forces, to correspond to the requirements defined by the ecological niche and the tasks.

IV. Design of Embodiment

Similar to the approach presented in [3], the design of embodiment approach is defined by the four steps **(1) modeling**, **(2) definition of goals**, **(3) parametrization**, and **(4) optimization**. The transfer of the embodiment concept, in terms of the principles introduced by Pfeifer et al., to a robot development process is initiated by the connection of each principle to these four steps of the considered optimization process.

a) The three constituents: Constraints defined by the three constituents (definition of ecological niche, definition of tasks, and development of the agent) are assigned to either one of the new subgroups **task and environment dependent**, and **task and environment independent** constraints. Constraints that are task and environment independent need to be implemented in the **model**. Task and environment dependent constraints must be considered only during the respective task or in the respective environment and are therefore required to be considered in the step of **goals**.

b) Complete agent: All elements of the complete agent (embodiment, environment, and information processing) interact with each other. Interactions between embodiment and environment in terms of contacts or impressed forces like gravity for example can be considered as passive control, and interactions between information processing and environment as active control. Both types of interactions must be taken into account by proper selection of a suitable model structure and the according parameters for the model-based optimization. A mutual adaption of parameters, which represent key properties of active and passive control is required to allow for an efficient operation of the robot. In the presented development process, this adaption is performed via the setup of **parameters**. Suitable structures for robot, interactions, and information processing are considered within the **model**.

c) Versatility: To meet the requirement of managing the complex ecological niche while achieving multiple tasks, a proper selection of multiple **design goals** must be defined, representing all tasks and implicitly defined constraints by the ecological niche. By necessity a multi-objective **optimization**, that includes multiple experiments, arises from the multiple goals in an optimization process. The evaluation and selection of optimal **parameters** from the set of optimal solutions during a complex decision process is therefore required.

A. Formulation of an optimization problem

The consideration of the extracted requirements can be combined to an optimization approach. The following paragraphs describe the relevant constraints from the principles to design an embodied agent for each optimization step.

a) Modeling robot and environment: Although no explicit advice is given for the generation of a model, important requirements regarding the structure of the model are stated by Pfeifer and Bongard. Different aspects of the presented principles need to be considered in the modeling of the robot and the environment:

- Task and environment independent constraints need to be considered in the model of robot and environment.
- The structure of robot, active control, and interactions with the environment must be able to perform passive control.

The model must include all elements of the robot, the environment, and the corresponding interactions, which are independent regarding task and environment. The structure of the active control must also be designed within this step.

b) Design goals of robots interacting with the environment: In the design of motion goals multiple principles need to be considered:

- Task and environment dependent constraints must be defined in the goals of the robot.
- To achieve a versatile robot, the definition of multiple goals based on the tasks and the ecological niche is required.
- The design goals must be defined to reflect the requirements and tasks of the robot. The requirements are defined through the ecological niche and the tasks.

To combine the design goals with the robot and environment model, a set of simulation experiments is generated. In these simulation experiments the robot performs the desired operation in varying configurations. The respective active control, consisting of feed-forward control and feedback control, must be applied during these simulation experiments.

c) Parameters for robot design and control: To perform a parameter based optimization of the model with respect to the defined goals, parameters are required to be defined. Different requirements must be considered for the parameters according to the principles:

- Active as well as passive control parameters are desired to be included in the set of optimization parameters.
- The parameters must be selected, such that all defined goals are achieved optimally. If multiple objectives are applied, a decision process to find the best suited configuration from the set of optimal solutions is typically required.

Before starting the optimization, the parameters which are taken into account for the optimization have to be selected.

d) Optimization of embodiment and classification of results: During the optimization the defined parameters are optimized with respect to the desired goals of the robot. According to the design principles, the optimization is subject to the following requirements:

- Active and passive control parameters must be optimized together in one optimization step.
- The ambiguity of the ecological niche and the applied goals call for the application of a multi-objective optimization approach.
- Desired motion behaviors must be ranked with higher value.

The resulting problem is a combined multi- and single-objective optimization. Task dependent parameters can be optimized independently for each considered objective, while task independent parameters must be constant regarding all considered objectives. To address the hybrid characteristics of the optimization problem, the optimization is approached as set of optimizations. For each inner optimization, task independent parameters are considered constant, while task dependent parameters (like parameterizations of active controls) are optimized. For the outer multi-objective optimization the set of Pareto optimal solutions is computed [8]. This approach guarantees to compare the optimal configurations of task-dependent parameters to find the optimal task-independent parameters for all considered objectives.

V. Application to BioBiped2 Robot

Therefore the design of embodiment approach is applied to evaluate the optimal configuration of the BioBiped2 robot for a running motion in this concluding example. The BioBiped2 robot [15] is a two-legged musculo-skeletal humanoid robot with series elastic actuation. It has three-segmented legs and no upper body. The actuation of the links is based on an antagonist principle. In this example the design of embodiment approach is applied to come to design decisions regarding the elastic elements in the series elastic actuators.

The BioBiped2 robot is desired to perform fast running on flat terrain. Furthermore the robot is desired to perform an efficient walking gait. Therefore it is necessary to find the optimal configurations of active and passive control parameters to achieve these motion goals. In the following sections the application of the design of embodiment approach is presented.

The design and setup of active and passive control parameters to achieve fast running and efficient walking in a two-legged robot is a complex problem, which cannot be addressed systematically with established approaches. The dimensioning of respective parameters in the real BioBiped2 robot is performed by manual adjustment based on expert knowledge and experiences. Since the real BioBiped2 robot is up to date not operational for in-plane locomotion, no experiences regarding the control parameters exist for comparison.

The received results can be used as initial set of parameters for a possible hardware-in-the-loop evaluation to achieve a running motion of the BioBiped2 robot or its successors.

A. Modeling robot, environment, and active control

For this example the Matlab Simulink SimMechanics model of the BioBiped robot, which was developed by Radkhah in [14], is used. This model is accurate and has been tested and validated with experiment results [14].

To allow for the application of the model in the considered scenario, the model is expanded by a state machine for active control. In the following, a brief assignment of the model to the defined categories is presented. This assignment is complemented by an introduction to the applied state machine. A more detailed introduction to the robot model can be found in [14].

- **Structure of the robot** The structure of the robot is modeled as chain of rigid links and joints. Each leg includes three links (thigh, shank, and foot) and three joints (hip, knee, and ankle). The legs are mounted via the hip joint to the torso. The actuation is performed by serial elastic actuators. These are mounted in order to mimic the dynamic properties of the most important muscles in human legs. In contrast to the human, the robot can only actively actuate the extension of knee and ankle, since only vastus (VAS) and soleus (SOL) are actuated. The retraction is passively performed by attached springs with constant elastic properties.
  It must be considered, that the simulation model does not include joint-angle constraints for the ankle joints. This difference to the real robot is addressed by the problem formulations however.
- **Structure of the interactions with the environment** Besides gravity the robot is affected by two types of interactions with the environment:
  - The robot is mounted, such that the torso can only perform translational movements in the saggital plane. No friction is assumed for the translational movement of the torso.
  - In order to achieve a legged motion, the robot must be capable to perform ground contacts. Each foot has two contact points: one at the tip, and the other at the heel. To calculate the required forces, the Hunt-Crossley model is applied [5], [14].
- **Structure of the active control** To address the formulated requirements to develop an embodiment agent, the active control structure is based on a state machine. This state machine is added to the existing BioBiped2 model, by implementing a new Simulink block and adapting the respective program for operation.
  Whenever a ground contact is established (touch down), or finished (lift off), a new set of target motor angles for every involved joint is set. The structure of the implemented state machine is depicted in Figure 2.
  The respective target motor positions (extend, retract, and prepare) for each joint are subject to optimization in the inner optimization.

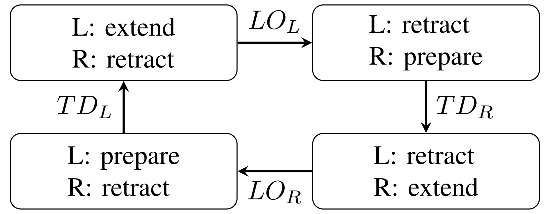


Fig. 2: The graph displays the structure of the state machine, which is applied for both motion goals in the present example. Overall there are four states, which are triggered by the lift off or touch down of either of the two feet. The state machine returns the respective target motor position for all involved joints (hip, knee, and ankle) for both legs. The labels LO and TD refer to liftoff and touchdown, while the respective index refers to the left or right leg.

B. Design goals

The target robot configuration is desired to be optimal with respect to two motion goals:

- **Problem formulation 1**: achieve a fast jogging motion
- **Problem formulation 2**: achieve energy efficient walking

The two problem formulations are discussed in detail in the following paragraphs:

a) Achieve a fast jogging motion: The robot is desired to achieve a fast forward motion with flight phases in-between the alternating ground contacts. The robot starts with no initial velocity at a height of 1 [m], regarding the center of mass of the torso. At start the left leg is in retraction state, while the right leg is in prepare state. The initial joint velocity is zero for each joint.

To evaluate the velocity, the achieved distance Δ_x at the end of a time period of six seconds is assessed. In this problem formulation the robot is desired to perform a jogging motion with flight phases. Therefore it is also necessary to reward flight phases in the problem formulation. This can be achieved by considering the duty factor. To prevent the robot from moving in the opposite direction, a penalty term is introduced.

$$Q_1 = \begin{cases} -10 \cdot \Delta_x + \text{duty factor} \cdot 10, & \text{if } \Delta_x < 0 \\ -\Delta_x + \text{duty factor} \cdot 10, & \text{else} \end{cases} \quad (1)$$

The objective is subject to minimization.

b) Achieve energy efficient walking: For the second motion goal, the robot is desired to perform a walking gait. Walking is typically characterized by the lack of flight phases and a low energy consumption. For this experiment the robot starts with an initial velocity of 0.5 [m/s] with a height of 0.72 [m], regarding the center of mass of the torso. As for the jogging motion, the initial configuration of the left leg is the retraction state, while the initial configuration of the right leg is the prepare state. Again the initial joint velocity is zero for each joint.

Besides a low energy effort and minimal airtime, a minimum distance must be accomplished. This minimum distance is set to 5 [m] in 6 seconds for this example. If the minimum distance is not reached or the robot is falling, which is identified by the torso height, a penalty term is introduced.

$$Q_2 = \begin{cases} 1000 * (5 - \Delta_x) + E + T_f, & \text{if } \Delta_x < 5 \\ 10000 + E + T_f, & \text{if torso}_z < 0.2 \\ E + T_f, & \text{else} \end{cases} \quad (2)$$

The time of flight T_f in this equation is the number of milliseconds without ground contact of at least one foot. The energy E is the overall motor power in [W] calculated by motor velocity times torque for each motor.

C. Parameters for robot design and control

Due to space restrictions, the list of constant parameters is not presented here. A complete list can be found wihtin the context of [14]. The following list will focus on the parameters, which are considered during the optimization processes.

- **Time dependent and switchable parameters**:
  - target angle in retraction state of ankle τ_{A0}, knee τ_{K0}, and hip τ_{H0}
  - target angle in preparation state of ankle τ_{A1}, knee τ_{K1}, and hip τ_{H1}
  - target angle in extension state of ankle τ_{A2}, knee τ_{K2}, and hip τ_{H2}
- **Time independent parameters**:
  - spring coefficient of knee extensor (VAS) k_{VAS}
  - spring coefficient of ankle extensor (SOL) k_{SOL}
  - spring coefficient of knee and ankle flexor (BF and TA) k_F

D. Optimization of embodiment

- **Inner optimization**: The inner optimizations were performed with the genetic algorithm of the Matlab optimization toolbox. The optimization settings are set as follows:
  - population size: 20
  - maximum generations: 60
  - function tolerance: 1e-14
  - nonlinear constraint tolerance: 1e-6
  - scaling function: rank
  - selection function: stochastic uniform
  - elite count: 2
  - crossover fraction: 0.8
  - stall generation limit: 8

	retract		prepare		extend	
	min	max	min	max	min	max
ankle	-4	0	-4	0	-4	0
knee	2	6	2	6	2	6
hip	-0.2	1.2	-0.2	1	-0.4	1

TABLE I: Here the applied boundaries of the active control elements are listed in [rad].

  The optimization was performed on an intel CORE i7 (2.67 GHz), 4GB RAM computer. The duration of each inner optimization process was between approx. 2 [h] and 3 [h]. The boundaries are chosen based on the motion capabilities of the BioBiped2 robot. To furthermore exclude undesired motions, the hip motor angle range is reduced.
- **Outer optimization**: To find the optimal configuration for each considered motion goal, two series of outer optimizations are performed. In each series of optimizations the following spring coefficients are considered:
  - spring coefficients SOL: 7900, 10000, 13000 [N/m]
  - spring coefficients VAS: 13000, 15400, 17900 [N/m]
  - spring coefficients BF and TA: 4100, 5800 [N/m]

  Overall this results in 18 combinations for each problem formulation. For each of these combinations an inner optimization is performed with the settings described above.

E. Classification of results of the example

The optimal objective values for each considered configuration are depicted in Figure 3. Figures 3a and 3b show the optimal values for problem formulation one: jogging, while Figures 3c and 3d show the optimal values for problem formulation 2: walking. To more conveniently visualize the three considered dimensions of parameters (k_{VAS}, k_{SOL}, and k_F), each plot shows a constant parameter for k_F.

Configurations which are evaluated in the simulation are marked with a black dot. Configurations which are Pareto-optimal are marked with a red dot. Both objectives are subject to minimization, therefore in every plot a smaller value is better. Table II shows the according objective values and passive control configurations of the four Pareto-optimal solutions. Tables III and IV furthermore list the respective active control parameters of the Pareto-optimal configurations for either jogging or walking.

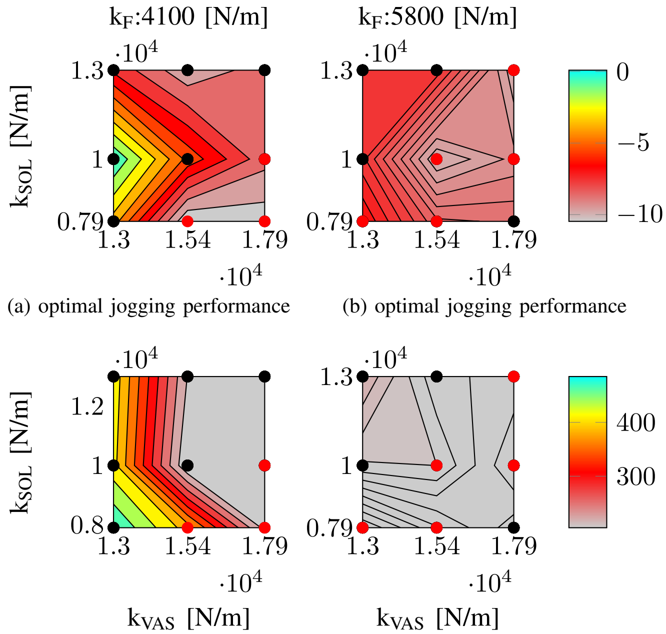
Finally the jogging and walking motion with respective optimal passive and active control configuration are presented as sequence of frames (see Figures 4 and 5). The frames are taken from an animation of the resulting motions. For the visualization, the animation tool from [14] is applied. The complete animations of jogging[1] and walking[2] can be found online.

The analysis of these optimal configurations (number 1 for jogging and number 4 for walking in Table II) depicted in Figures 4 and 5 reveals, that each desired motion goal requires a different passive control configuration. For jogging the knee actuator must be equipped with a stiffer elastic element, while the ankle and both antagonists require a softer spring. For walking a softer knee actuator elasticity is preferred, while the ankle and antagonists are equipped with stiffer springs. The two desired motion goals therefore do not have a unique solution regarding the configuration of the passive control elements.

F. Evaluation of requirements for embodiment

- **Three constituents:** *The requirements in form of ecological niche and desired tasks of an agent, need to be*

[1]http://youtu.be/GfJiyzFVm_w
[2]http://youtu.be/0XHmlTrj2FU



(a) optimal jogging performance (b) optimal jogging performance

(c) optimal walking performance (d) optimal walking performance

Fig. 3: These plots depict the optimal objective value for each considered spring configuration. Figures 3a and 3b show the optimal values for jogging, according to Equation 1. Figures 3c and 3d show the optimal objective values for walking, based on Equation 2. Evaluated configurations are marked with a black dot, while Pareto-optimal configurations are marked with a red dot.

	Q_1	Q_2	k_{VAS} [N/m]	k_{SOL} [N/m]	k_F [N/m]
1	-10.473	386.601	15400	7900	4100
2	-10.091	348.923	17900	7900	4100
3	-9.130	331.132	17900	10000	5800
4	-7.463	310.897	13000	10000	5800

TABLE II: The table lists all Pareto-optimal configurations of the investigated solutions regarding the two problem formulations jogging (Q_1) and walking (Q_2).

	τ_{A0}	τ_{A1}	τ_{A2}	τ_{K0}	τ_{K1}	τ_{K2}	τ_{H0}	τ_{H1}	τ_{H2}
1	-1.90	-0.09	-2.04	2.91	2.98	4.63	0	0.60	-0.01
2	-1.90	-0.09	-2.03	2.91	2.9	4.73	0	0.60	0.03
3	-0.67	-0.44	-2.72	2.72	4.39	5.82	0.09	0.41	-0.05
4	-2.72	-0.45	-3.03	3.07	3.75	5.78	0.03	0.77	-0.01

TABLE III: The table lists the target motor angles in [rad] for jogging motion of the Pareto-optimal passive control configurations.

	τ_{A0}	τ_{A1}	τ_{A2}	τ_{K0}	τ_{K1}	τ_{K2}	τ_{H0}	τ_{H1}	τ_{H2}
1	-1.66	-0.37	-0.96	4.36	3.77	3.88	0.03	0.93	0.54
2	-1.66	-0.87	-0.93	4.35	3.77	3.71	0.03	0.91	0.54
3	-1.46	-0.87	-0.93	4.38	3.85	3.77	0.04	0.88	0.62
4	-1.53	-0.99	-0.93	4.35	3.77	3.72	0.07	0.88	0.64

TABLE IV: The table lists the target motor angles in [rad] for walking motion of the Pareto-optimal passive control configurations.

considered in agent development
This example features a detailed mathematical model of the considered robot and the relevant dynamical interactions with the environment. Together with the description of the desired motion goals, all three constituents are considered.

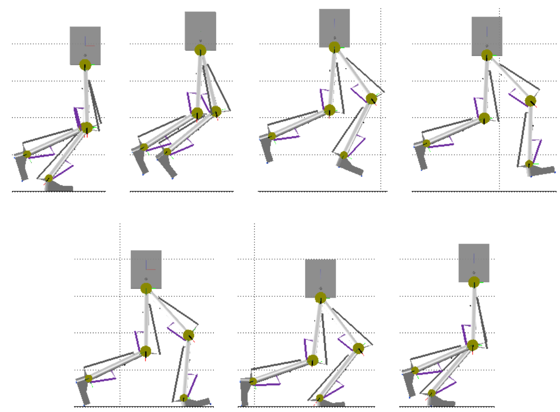


Fig. 4: The sequence shows the robot motion with the optimal configuration of active and passive control parameters for jogging (configuration number 1 in Tables II and III).

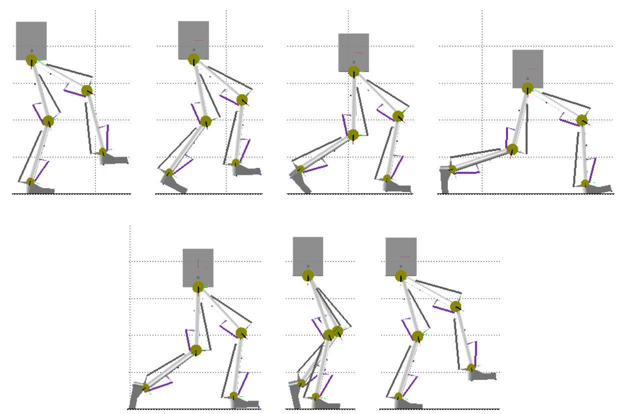


Fig. 5: The sequence shows the robot motion with the optimal configuration of active and passive control parameters for walking (configuration number 4 in Tables II and IV).

- **Complete agent:** *Both the interactions between embodiment and environment (passive control), as well as the interactions between information processing and environment (active control) need to be considered in agent development.*
  During the simulation process all relevant interactions with the environment and all respective reactions of the robot embodiment are considered. Moreover a complex state-machine based control approach is included to enable active control triggered by ground contacts. A comprehensive consideration of the complete agent is therefore guaranteed.
- **Versatility:** *Prefer passive control over active control while maintaining the required versatility of the agent defined by ecological niche and tasks.*
  Each considered motion goal requires a different passive control configuration for optimal performance. This information is required to apply strategies for ambiguous multi-objective solutions. By means of these approaches

the required versatility can be achieved.

G. Discussion of example results

This example presents the application of the design of embodiment approach to a complex problem. The considered BioBiped2 robot is desired to achieve optimal performance, energy efficiency, and versatility by performing fast jogging and energy efficient walking. These motion goals are addressed by the dimensioning and setup of passive and active control elements. For that a complex simulation model of the BioBiped2 robot is extended with a state machine. Suitable active and passive control parameters are selected and optimized in the subsequent optimization.

The assessment of 18 relevant passive control configurations for each considered motion goal reveals a set of Pareto-optimal configurations (see Table II). The analysis of these configurations shows, that the optimal configurations for the considered motion goals (number 1 and 4 in Table II) present an ambiguous solution. To achieve optimal jogging and walking with the BioBiped2 robot, strategies for ambiguous solutions in multi-objective optimization problems must be applied therefore.

The subsequent evaluation shows, that the resulting configuration of the BioBiped2 satisfies the requirements for embodiment. The robot structure, the state-machine-based active control, the series elastic actuation concept, and the optimal active and passive control parameters provide for the adherence of all principles of embodiment. In the optimal configurations, the active and passive control elements work together best to increase the performance, versatility, and energy efficiency.

VI. Conclusion

This paper presents a systematic approach to the design and development of bio-inspired legged robots with highly compliant joint actuation based on a formalization of the eight main design principles for embodied agents proposed by Pfeifer and Bongard [11] and a proposed ninth principle, efficient versatility. In this paper the most relevant of these design principles are analyzed and amplified regarding the application for the design and setup of a complex musculoskeletal bipedal robot with tendon driven active and passive series elastic actuation.

A mapping of these principles to a multi-objective, and multi-experiment optimization approach for a multi-body dynamics simulation guarantees the consideration of every requirement stated in the list of principles. To enable the consideration of the principles to design an embodied agent in the design of embodiment approach, several new concepts and perspectives are introduced. These comprise for example the introduction of the term passive control for directed variation of the system behavior by mechanical elements, to enable the consideration of effects, which influence the behavior of a robot, but are not actively controlled by information processing. To address the problem of multiple motion goals, which often require opposing control properties, the principle of efficient versatility is introduced.

In established approaches the interplay between passive and active control and dynamics of robot and environment is typically difficult to consider in a satisfactory manner, which is a key feature of embodied agents. The proposed design of embodiment approach aims for a systematic consideration of all of these effects.

Finally the capability of the new approach to setup active and passive control elements for complex legged robots is demonstrated through successful application to the musculoskeletal BioBiped2 robot. By considering the evaluated guidelines in the development process, an embodied agent is developed.

Acknowledgements

This research has been supported in parts by the Research Training Group 1362 funded by the German Science Foundation DFG. The authors thank K. Radkhah for use of the highly capable BioBiped simulation model [14].

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