An Autonomous Biped
Concept and Design

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Abstract: This paper argues for a new approach in the mechanical design principle for the humanoid walkers. Applying linear electric direct drive motors the biped mechanism is able to behave as dynamically highly reactive walker admissible to exploiting its own natural dynamics. Based on this, a whole new concept of an anthropomorphic walker prototype is described including the interaction of the design and algorithmic aspects of the motion control.

1 INTRODUCTION

Bipedal walking mechanisms, once curiosum, today are multiple demonstrated devices. Drive of the development is manifold: the scientific understanding of the human walking itself, the engineering motivated technical demonstrations, medical applications in service of man, applications in military and probably further industries. Today walking has been demonstrated numerously but not to the expected satisfaction. It seems that the recurring design efforts copy the template of already working solutions. Also there is a lack of understanding the walking principles itself, despite a long history of biomechanical measurements (Osuka 2005; Geyer, 2011). The design task is a challenging one since several factors interplay. Any device which needs upright balancing while it is not fixed to a base is challenging to control; the control of the same device which is not only needs static balancing regime, but it is needed to move around in human walking like fashion is not understood and several control algorithms are not adequate to produce confident locomotion. The mechanical design from the available mechanical components is not self-evident either. Research is often necessarily constrained into one of these particular fields and the task is seldom regarded as an interrelated and integrated task. This is due to the fact that each subtask in itself is a challenging one. This position paper summarizes the design concept of a new type of biped design.

2 PREVIOUS WORKS

From mechanical point of view, the obvious aim of achieving human like walking for research class bipeds have been approached from diverse perspectives. It is centered on the dilemma how to integrate the available actuators into the embodying frame, which does the walking.

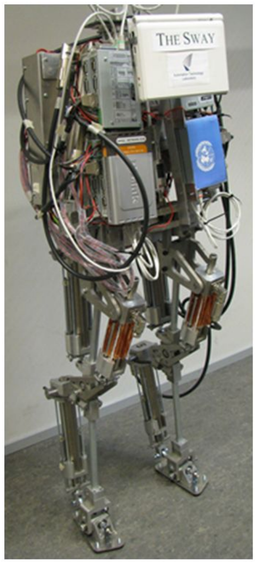

Figure 1: The SWAY, a bipedal autonomous walking robot.

Though the diversity is large, there are some typical solutions. Widespread solution among the humanoid type walkers, such as Asimo, is a Cardan

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style cross joint, where the motor is closely placed or integrated into the joint (Hirose, 2007, Honda Online, Lim, 2007, Akachi et al., 2005). Another solution is to employ transmission from a distantly placed motor to the joint. Such is for example the BiMASC legs (Hurst et al., 2007). Yet other solutions are the application of the linear actuators like pneumatic cylinders (Muscato, 2005), ballscrew actuated drives or series elastic actuators (Robinson et al., 1999).

In all cases the heart of the problem is the insufficient directly available torque of the rotational electric motors in small volume which would then require gears or other mechanical torque amplifiers. As a consequence either the coefficient of efficiency would dramatically drop or otherwise special arrangements are needed for the larger motor's placement. The application of gears substantionally alters the dynamic properties of the controlled mechanical equipment making it less reactive to the control signals and more power intensive to achieve a dynamic walking. Various recommendations to use linear motors seem to recognize these problems, but either the pneumatic or hydraulic actuators have their own drawbacks in the human type walking imitation. Though, the very same actuators may seem successful in a larger category walking devices, e.g. quadrupeds.

Another aspect is the interrelation between the available mechanical designs with the sought control algorithm. The conventional Zero Moment Point (ZMP) method requires large flat soles, the motion is a result of intense position or force control and not meant for fast motion (Vukobratović, 2004). The dynamic motion type algorithms assume light construction and relatively weak motors. Several dynamic walking algorithms applied to kinematically not enabling designs, where the control algorithms either necessarily distorted to deal with the extra dynamic load posed by the given mechanism or should use exaggerated driving forces, circularly increasing the inescapable mechanical burden for itself.

Sardain et al. has reviewed the typical mechanical architectures of the biped robots in 1998 (Sardain et al., 1998). Since then the basic approaches haven't changed except one notable exception which is the PETMAN of the Boston Dynamics company (National Research Council, 2008). In most cases the motivation is to create a mechanism for a given premeditated control concept which is typically the ZMP approach. In another case the type of mechanism is premeditated and the theory was created afterward to explain the motion. These are the passive dynamic walkers where the Limit Cycle Walking (LCW) concept has been worked out. In the third group the PETMAN robot takes its root from jumping devices where the design concept and the theory complement each other. In yet another group a premeditated theory is being applied to given robots not specifically designed for exploiting the control concept. The Biomechanics field is dealt with to explain the human motion based on experimental observations. It does not vindicate itself the task to design and construct human like mobile devices.

These efforts are largely have been influenced by the available resources. The aim of the most laboratory walkers is purely to demonstrate walking with a particular control concept on limited budget. These walkers are typically small, lightweight prototype where actuations are economized. These are proof of principle models, based on minimalist design on low budget. As such they are very much constrained in functions. Industry backed research does not limit the effort on mechanical design necessary be applied to for a given control principle. These are characterized on recurring control efforts and well established control algorithms. Biomechanics research has traditionally conducted in universities with support of medical industry, but their demonstrators are not meant to create full fledged walking devices rather particular orthoses to help locomotion. In our approach we are motivated by the human body and control principle, and trying to come up with a mechanical design on that principle.

3 THE DESIGN CONCEPT

3.1 Design Objectives

The currently established aim is to accomplish a human like walking, in style, in size and in efficiency. This is best approached by human like mechanical design. Previous walkers typically walk on flat, even surfaces some can cope with mild slopes and some can climb stairs. Moving on soft or irregular terrain however raises the issue of adequate mechanical design and control algorithms (Vukobratović, 2009). Though hands are naturally comes and utilized for the human walking they are not essential for our purposes. Immediate application areas of the human like design are in the rapidly developing robotics fields like the Geminoid robots, military and additionally the planetary humanoid robots.

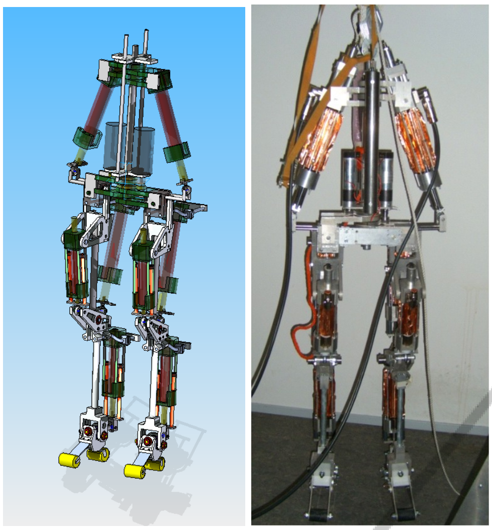


Figure 2: The skeleton design concept and realization.

The design objective is an energy efficient motion in general. As such we took example from the human body to achieve this goal. The biomechanics field has studied and unveiled the human motion characteristics in details for several decades. However its synthesis will become possible only with the developments of new powerful actuators.

Recently some actuators available in both commercial and research realms which suitability worth to explore for dynamic walking. In fact having the technology, custom made actuators of similar techniques are fully possible. New materials techniques and biomimetic actuators (Delude, 2005) carry considerable promises but they have not been explored yet in this applied mechanical field; thus this technology-base allows a limited improvements in the humanoid technology. Instead of optimizing (mainly in parameters) an existing conventional design we resorted to the vision of human motion by abandoning the conventional design patterns and by creating a mechanism functionally analogous to the human one. Replicating the human motion has two main aspects. The main mechanical characteristics are easily adopted but clearly there is a very sophisticated controller counterpart what the human brain does. Simply, it can be either captured for example by a neural network based controller as patterns, or the sequential motion primitives and their relations can be more carefully analyzed from mechanical point of view and understood. Understanding can lead to a simplified and energy efficient control.

One of the main characteristics of the human motion is the utilization of the natural dynamics and reckoning with it through motion primitives ahead. The result is a minimal effort control sequence, even utilizing the momentary (or indeed foreseen) interaction with the ground. From these follow that minimal but well chosen forces are sufficient for the locomotion. This allows us to venture to create a mechanism and later a control algorithm to achieve the energy efficient motion following the principle of the human locomotion.

After substantiating the design ideal into the skeleton design concept, we describe an achievable control algorithm exploiting assumed specificities of the walking mechanism. Then we describe the embodied walking mechanism, named THE SWAY, we analyze its mechanical features based on their utility for enabling high dynamic mobility control. After the kinematical and dynamical characterization of the mechanism, the controlling system architecture is outlined.

3.2 The Skeleton Design Concept

Though there is seemingly little difference among those design concepts which tries to create a humanoid like device, but the difference actually creates a new class of walking robot with new kind of capabilities.

The selected design concept follows an anthropomorphic plan: a well separable human size skeleton is actuated by detachable motors, whereas the skeleton is a carrier for motors and all auxiliary devices needed for autonomous operations. This is illustrated by the Figure 2. The skeleton is a standalone mechanism in itself capable of balancing and its uncontrolled motion is similar to human skeleton. Though this is an all-embracing intention, engineering inevitability would shape the skeleton accordingly. The skeleton has few but essential internal constraints, in the hip as well in the knee. The skeleton is human size, including a human shape foot. The motors are electric, linear, direct drive actuators and in principle detachable from the skeleton. Actually, the present concept was motivated by the employment of the electric linear direct drive actuators.

In Section 3.3 we elaborate on the advantages provided by the mechanism design while the mechanism itself will be detailed in Section 4.

3.3 Control Algorithmic Aspects of the Mechanical Design

The early works were more occupied with the control algorithm itself to create the walking behaviour, not realizing that the object which the algorithm is acting on will have an influence on the algorithm itself.

Traditionally several control concept able to generate stable walking. These are the ZMP, LCW, Dynamic Programming, Central Pattern Generator, Genetic Algorithm, Neural Networks, trajectory tracking etc. These are however treating a walking task process like, they result in a long sequence walking patterns. Our aim is to be aware of the biped dynamics in every moment and be able to govern it at will. Such control results in postural balance, walking initiation, gaining momentum, slowing down, turning, halting behaviours within the walking behaviour. For such a goal the above approaches are less suitable. We aim to apply methods where the biomechanical consideration can be quantified and governed. Such approaches are e.g. the momentum control and reflex control. We investigated an approach where the walking state has been divided into a network of neighbouring microstates, which covers all plausible dynamic states in which the set of admissible control actions known to be achievable and would lead the robot dynamics into the neighbouring state. Then the network of such states would realize the walking behaviour in whole. A test of it demonstrated in the Section 6.1.

The proposed mechanical design concept allows the following operation, described for a swift walking mode, as an example. Starting from a configuration, where the swing leg's heel touches the ground, the impact is taken up by the shank motor which smoothly curves the abrupt change of the angular momentum vector toward the next ballistic phase. This action is fully controllable according to the walking principle. At this point the support and swing legs' role swapped. The support leg's knee is self locked under the weight of the upper body. The upper body vertical orientation is regulated by the support leg's thigh motor, while all the motors on the swing side are free and unactuated. Advancing the body's forward motion the upper body sways toward the support leg where an internal constraints prevent further leaning sideway without any actuated effort and control of a motor. Meanwhile, the swing leg's shank motor pushes the upper body to gain momentum, while all other motors are free, since the support leg's motion is being driven by the inertia of the upper body. On the next state, the knee motor raises the shank to provide clearance between the foot and the ground to pass the swing leg forward. The support leg's thigh motor regulates the upper body vertical orientation while the ankle and knee remain unactuated. Next the swing leg moves forward while forming an underactuated system to drive. During this motion the robot tends to fall toward the swing leg without actuation. When the swing heel touches the ground the cycle is recurring. Then the biped works on the following principle: the gravity actuates, inertia drives, constraints direct, motors correct. Since the dynamics is analyzed at each microstate a proper calculated driving or correcting action could take place.

The main driving force is the gravity while joint actions fulfil the role of coordinating the constraint actions. Since the inertia takes the body with it, passive joints move in trajectory free fashion. In other words the motion control task becomes to plan the actions of the expected internal and external constrains based on the dynamics of the biped. The symbiosis of mechanical design and the control principle eliminates the need for force sensor instrumentation; nevertheless this information is easily derivable from the dynamics if so needed.

The enabler of the minimally actuated motion logic above is the proposed mechanical design as detailed in Section 4. It is also applicable for extraterrestrial locomotion on soft or rough terrain e.g. the Moon's or Mars'.

4 THE MECHANISM

4.1 System Overview

The design process, regardless whether it is based on systematic or intuitive approach is a highly personal, creative and recurrent process. It is well manifested itself in the variety of the designed bipedal walkers in the past. Our design approach is to choose the characteristically human kinematic and dynamic features to follow. In addition the design ought to facilitate the direct miming of the human walking style. The following factors determine the uniqueness of the proposed design:

1. weight bearing skeleton as a functional element,
2. skeleton carries detachable motors,
3. bisected hip design on a spine,
4. mechanical motion limits in knee and hip; when those are engaged they release or replace actuator efforts serving functional purpose for the control,
5. utilizing linear electric direct drive actuators, and a
6. control algorithm which meant to utilize the

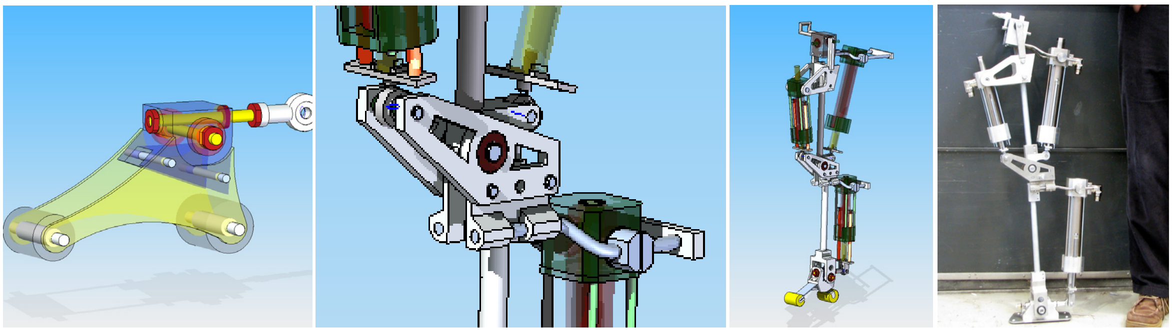


Figure 3: The foot, knee and the leg assembly.

natural dynamics of the mechanism, which is focusing on a smooth transition of the upper body part, having appropriate inertia.

The skeleton is compiled from simple aluminium tubes to replace spacious casing. The tube elements have diminishing weights but have sufficient strength to carry the body. Thus the enabling specificity is that the robot has no separate carrying frame incorporating the motors and the joints, rather it has functional elements (skeleton and motors) separately – intentionally mimicking the human structure (Figure 2).

4.2 Mechanical Architecture

4.2.1 The Actuators

Pneumatic and hydraulic actuators have been used to create muscle like linear actuation earlier. They are both powerful actuators but require extra complexity for their infrastructure. Hydraulic actuation has all the advantages of strength and size. However the robot should have closed hydraulic circuit and the pump on board with auxiliary components placed on the trunk.

Rotational electric DC motors are widely employed in the contemporary walkers. To achieve strength it should employ high ratio transmissions typically harmonic drives. However in this case the actuator looses a direct connection to the actuated mechanism injecting huge reflecting inertia and friction and thus the whole walking mechanism 'looses dynamics' a chance to the inertial control. A chance, that the gravitational inertia is a direct actuation force, rather than an effect which should be compensated by the control algorithm. This necessitates employing position control of the DC motor versus a current control producing direct torque. Nevertheless, with rotational electric motors, linear motion can be generated. Notably series elastic actuators can provide strength and compliance between the actuated constructional elements. But beside the problem of producing higher force, which would need higher strength motor, thus heavier and more sizeable motor, the long term operational issues like wear, thermal balance also come forward. With high transmission ratio the agility of the actuation is lost.

Linear electric direct drive motors are new comers in the biped field, and not tested for this application. They evade the disadvantages of the above actuation types. Comparing with the hydraulic pistons they are somewhat bigger and much weaker, but as a system element much more economic in terms of total weight and size occupancy. The linear electric direct drive motors have better dynamic properties and simple direct output force control capabilities. Since its force output is limited, the question arises, what control approach is possible at a limited force budget. The proposed solution to this quest is to design such a mechanism which minimizes the need of exciting the dynamics of the mechanism and let the external and internal forces act such that the walking trajectory will be resulted by the robot's own natural dynamics but guided by the actuation forces. This is motivated by the observation that at habitual walking the man is taken forward by its own inertia and not by continuous force efforts. Then applying the liner electric direct drive motors to the control concept of Section 3.3, its feasibility has been tested by simulation and practical tests (Section 6). The linear motors are placed so on the mechanism that it optimizes the availability of forces from the actuators along its motion interval, as the function of the desired forces due to the dynamical task requirements. A well designed control system then allows introducing programmed compliance between the machine elements, as well as facilitating to the energy recuperation from the walking motion. We have acquired commercial-of-the-shelf LinMot linear

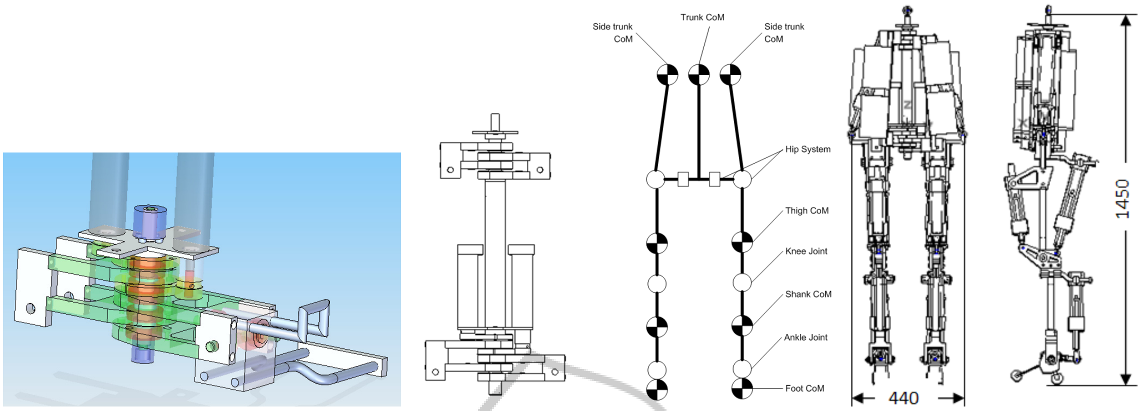


Figure 4: The hip and hip joint, hip and shoulder on the spine, kinematical scheme, trunk and biped with measurements.

motors which are permanently actuated synchronous servo motors for this prototype (LinMot Online). Use of custom made linear induction motors also matches the design concept. Further motivation of linear actuators is that with the advance of nanotechnology and microprocessing, advent of artificial muscles can be expected in the future (MYOROBOTICS, Delude, 2005), which would compactify the placement of the future linear actuators. According to our other application intention, extraterrestrial bipeds on the Moon and Mars can be actuated by linear electric direct drive motors, which place emphasis on the correct dynamic control with reduced need for static force budget.

4.2.2 Foot and Ankle

The foot provides contact to the ground and the ankle would activate the robot. Several authors assign fundamental role to the shape and function of the foot. Indeed the foot is which smoothly shapes the momentum of the whole biped at every step into its desired controlled direction. Its shape, design, mechanical properties have been designed diversely.

The conventional ZMP control principle requires specially instrumented flat foot design – for typically moving on even surface. The foot typically made as a flat metal element supposing that the robot places the whole sole from above vertically, then when down, the whole robot is pivoting around the support leg's ankle. Occasionally the foot is morphed to the human foot shape or a real shoe is put on the foot. In other cases the toe is made to be rotated around and increases the surface of contact while executing leg pushing or the heel is shaped to absorb the orthosis' impact. Some authors (Geyer et al., 2006) also incorporate the leg compliance as a key to the walking principle.

The proposed ankle is powered in the sagittal plane, but it is not powered in the frontal plane around the roll axis. This still allows a forward propelling motion and it also can exert forces for other kind of motion primitives (i.e. postural balance and stepping). The sideway actuation is obsolete in this dynamic walking approach (as opposite to the ZMP walking approach) since the biped locomotion principle does not require it. In extreme case, walking with stilt does not require at all a powered foot. However the anthropomorphism is important in our case. We employ rubber cylinders of proper grade for this prototype to provide good stiction to the ground. The toe is utilized for leg pushing and the heel for absorbing landing impacts. The rubber cylinder passive compliance accommodates to the unevenness of the surface and the weight shift of the mechanisms as it walks. The shank motor handles both the impact at heel touch down and the leg push with the toe, together the passive foot, eliminating the need of built-in design and control complexities. The shank motor arm is placed higher to allow a firmer stance of the sole on the (uneven) ground when standing or when the shank motor pushes the toe when walking. This prototype however oversimplifies the foot design at the expense of emphasis their main functions.

4.2.3 Knee

The knee design is the other most important element which influences this walking concept. The knee has a sole function to raise the shank to make clearance when the swing leg is brought forward. At the conventional solution the support leg's knee actuation also should oppose the significant static and dynamic forces. Some solutions use programmable mechanical locks to eliminate the need for actuation. In our proposal we mimic the human knee function constraining the joint motion in the forward moving direction just a little bit over the vertical neutral position. With this the robots own weight locks the knee without any actuation when standing still and when the stance leg follows the trunk motion forward.

4.2.4 Thigh and Shank

The main design elements in the thigh and the shank are the load carrying bones. Linear motors are suspended on that structure. The thigh motor has two functions. When the corresponding leg is on the ground it exerts torque on the trunk, otherwise the same motor raises and swings the leg. A cantilever introduces limited flexibility between the actuator and the major upper body mass. The thigh joint limits the allowable swing of the leg and it can be designed for various values. If the shank motor neglected the biped should walk as on stilts.

4.2.5 Spine

The main constructional element is the spine (Figure 4). It carries any other elements. The main design coordinate system is attached to this element. It is simply a tube.

4.2.6 Hip and Shoulder

From design point of view, the placement of sizable powerful motors while ensuring the desirable kinematic functionality is the central problem. To resolve this issue several unique approaches have been proposed. Our solution is shown on Figure 4. It is a bisected hip. Its sides are directly connected and rotating around the *spine*, with double function to rotate and hold the hip joints. To increase the rigidness and reduce the weight these identical elements are split and interlaced with each other. Each side of the hip is actuated relative to the spine by DC motors. The hip carries a two degrees of freedom hip joint, which in turns carries the thigh.

The hip's task is either to ensure change of the trunk position relative to the ground when the robot is standing or allows the legs move relative to the vertically kept trunk when the robot is walking. Considering the idealized closed loop of the kinematic chain formed by the two hips and legs and the ground, difficulties might arise, since legs' geometric constraints cannot be always satisfied. This issue however will be eliminated by the foot flexibility.

The hip and the shoulder design is analogous. The shoulder carries the waist actuator. The waist motor connects the upper shoulder and the hip joint. The hip joint constraint in lateral plane is realized by limiting the waist motor stroke – simplifying the hip joint. This constraint plays a functional role as described in Section 3.3. It also releases the waist actuators from any large counterbalancing efforts.

4.2.7 Leg

The leg (Figure 3) as an aggregate is built from the hip joint, thigh, knee, shank and foot.

The leg can be slightly pulled beneath the trunk, allowing minimizing the *sway* of the torso while walking, eliminating the counterbalancing forces and dramatically changing the character of the walking, with favourable consequences for the algorithm sophistication and the energy consumption.

4.2.8 Trunk

The trunk (Figure 4) as an aggregate is built around the spine. The trunk comprises the hip and shoulder at the two ends of a connecting spine. The trunk and thus whole robot is composed from two identical and symmetric parts rotating around the spine axis. The trunk is also a carrying element for the motor controllers, the computer infrastructure, the sensor and the energy subsystems which are built on a slightly displaceable chest element whose rotation axis shares the hip joint axis on both biped sides. Its presence is not inevitable but helps to modulate the biped's swaying motion. Additional elements like batteries, various electronics and computers connected to the spine.

No separate casing for the trunk is designed, thus the legs are not connected to a common base. The hip and shoulder are bisected and the corresponding joints turning relative to the spine. This resulted in a solution, where (i) mechanically, the constructional elements are minimized, since only the actuators, the joints and minimal additional material are present; and (ii) functionally, where the two halves of the biped are independently suspended from a central spine. Turning will be similar to the human, where the whole torso making the turn exploiting the stabilizing effect of the body's inertia when controlling the turning.

4.2.9 Additional Elements

The whole robot is built from aluminium parts except the small parts like ball bearings, etc. The joints can contain flexible, vibration damping sockets between the structural machine elements. Furthermore explicit energy conserving springs also can be easily accommodated into the mechanism since the linear motors can automatically comply to the displacements when force control is applied.

4.2.10 The Biped

The biped (Figure 4) is an aggregate of the legs and the trunk. The construction is modular, and care has been taken to use the simplest functionally necessary machine elements for each module. Additional elements are the cabling, add-on sensor and control devices, which introduce perturbations for the control algorithm.

Our kinematic and dynamic analysis is based on the geometric and physical description of the biped's CAD model (Table 1). Rotation angles can be linearly approximated as a function of the stroke with rms less than 0.01 rad in the operation range of the joints, simplifying the calculations. The overall system specification (Table 2) is to be compared to Asimo specification (see the References section).

5 COMPUTER SYSTEM ARCHITECTURE OUTLINE

What follows is a preliminary control system design for the above described walking mechanism. The system is build up from 'independent' subsystems (modules). Independent in the sense, that their functionality constrained to a topologically separated module; they are developed and tested independently; and they can be replaced by another similar module without changing, at least significantly, other subsystems. Thus the robot has the following subsystems: mechanical, energy, sensory, control, motor, HMI, safety, actuator units, and the walking algorithm domain. The information flow between the subsystems is realized by the computer infrastructure.

The biped's computer infrastructure (Figure 5) encompasses hardware and software, and when it combined with the mechanics it constitutes a controllable device. It contains a central computer (CC), human machine interface (HMI), energy subsystem (ES), sensor subsystem (SS), a walking algorithm computer (WAC), a motor hub (MH), motor controllers (MC) and motor drivers (MD). The *CC* supervises functionality of all modules. It is an autonomous unit (GumStix), permits and oversees the robot operation, checks the operability and status of all other subsystems, also can decide

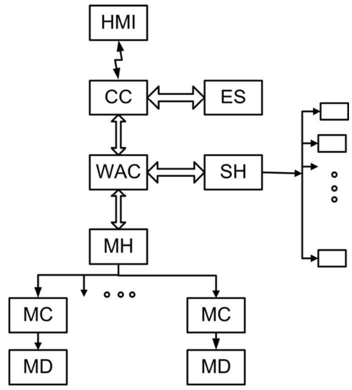


Figure 5: The Sway biped, modularized computer infrastructure.

and able to shut down the system. It has own logic to decide and overview (based on network messaging) what constitutes a normal operational regime of the robot. The *WAC* (EEE 901 PC) is occupied strictly only with the logic of the experimental walking algorithm. Its input is the sensory and the user's command information. It outputs a compact motion command to MH. The *SS* centers around the SensorHub (SH) (PC-104), which acquires, process and stores *all* sensory information of the robot. It is connected to the WAC. (In our experimental embodiment the motor controllers directly can have access to the sensor data). The SensorHub operation is programmable by the WAC. The communicated sensor data, and the choice of sensor data processing with parameters are selectable, events are parameterizable, etc. The *MH* (PC-104) distributes and oversees all motor related communications, trajectory generation, scheduling and diagnosis. The *ES* (PC-104), designed for an independent working. Among its functions are to manage the battery units, as well as roles in the regenerative control of the actuators. The safety subsystem monitors the resulted actions of selected modules. It relies on common sense self-diagnostic elements of the other subsystems: energy supply, range of actuator motion, stability of motion, motors' and computers' health, etc. Each computer units are implemented by the least necessary category microcomputers. Chiefly CAN, but ad hoc Ethernet and SPI networking have been used.

6 FROM CONCEPT TO CONSTRUCTION TESTS

To gain confidence of the suitability and the expected dynamic behavior of the biped the assembled mechanism underwent several tests on different level.

6.1 Simulation Studies

The simulation studies have been carried out in Matlab/Simulink/SimMechanics environment.

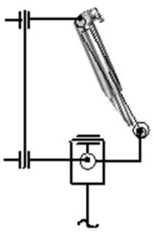
6.1.1 Oscillatory Motion in the Frontal Plane

The frontal motion test includes testing the logic of the rocking motion in the frontal plane, the availability of the motor strength to rock the whole biped and testing the effect of the hip limit constraint. In one test the stance of the biped has been decreased, correspondingly the need for the waist motor actions to drive the rocking motion has been reduced. The lateral oscillation has been sustained by the stepping motion of the legs. This test shows that while inclining the design toward instability the needed driving efforts are reducing while the need for the agile motion control is increasing

Table 1: Main Kinematic and Dynamic Parameters of the Individual Body Segments.

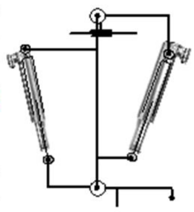
Trunk

Length	0.405 m
Joint limits	-5°↔ 30°
Rotation angle approximation	-3.63 + 9.67 x
Maximum Actuation	585 N
Mass	25.8 kg
Principal mass inertia [kg m^2]	(0.89, 0.64, 0.43)



Thigh

Length	0.45 m
Joint limits	-30°↔ 30°
Rotation angle approximation	2.24-6.22 x
Maximum Actuation	585 N
Mass	9.81 kg
Principal mass inertia[kg m^2]	(0.25,0.28,0.03)

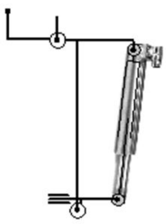


Knee

Joint limits	5.5° ↔ -45°
Rotation angle approximation	-3.1+12.16 x
Maximum Actuation	255 N

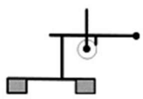
Shank

Length	0.45 m
Joint limits	-30°↔ 30°
Rotation angle approximation	3.64 – 10.36 x
Maximum Actuation	585 N
Mass	7.58 kg
Principal mass inertia[kg m^2]	(0.25,0.28,0.03)



Foot

Length	0.05 m
Mass	1.19 kg
Principal mass inertia[kg m^2]	(0.001,0.002,0.002)



6.1.2 Step in the Sagittal Plane

Motion in the sagittal plane gives a qualitative judgment of the dynamic behavior of a massive object with a possible control algorithm. While the final 3D motion generation is different, we implemented the elements described in Section 3.3. Simulation trials, which resemble Moon and Mars environment with reduced gravity and soft ground, have been also carried out for the proposed design.

6.1.3 Homing Calibration

In physical systems the exact position of center of masses of the body elements for the finally prepared prototype are not exactly known. Homing creates a reference configuration where the robot could stand with no actuation without collapsing. Homing is complemented by simple mass measurements to create an approximate dynamic model for the biped. Homing is based on minimizing the shank and thigh motors' current which keeps the biped in a vertical stable position without actuation.

6.2 Practical Tests

The motors have been tested individually for function, strength and agility (Peralta et al., 2009). Then collective test of linear motors has been carried out producing stable postural balance around zero nominal current actuation, actuating the thigh and shank motors under LQR on one side, maintaining a stable posture even when manually shaking the biped and all other joints were unactuated. When the sagittal stance formed a triangle with the legs the robot could produce a stable balance with a sole thigh motor actuation while all others joints were unactuated. The waist motors of the biped were tested which overwhelmingly could overturn the robot sideway.

Motor thermal behaviours were tested by static and dynamic tests for the most loaded motors. Thigh motors withheld the fully stretched leg in the air for several minutes without warming. The knee motors could intensively raise and lower the shank several tenths time before the temperature limit is reached and the motor controller cut its operation. This behaviour is due to the lower grade commercial off-the-shelf motor, selected intentionally, which force constant is half of the thigh's motor. This issue has been fixed by cooling the motors and applying a preloaded spring to the knee. The motor change however is not necessary to conduct tests of limited

Table 2: The SWAY specification.

Weight, operational	Up to 65 kg
Walking speed	0-0.8 m/s
Walking algorithm	Dynamic walking algorithm
Actuators	8 linear electric direct drive motors, 2 DC motors
Control Unit	Distributed control centers for HMI, central computer, walking algorithm, motor control hub, distributed local motor controllers
Sensors	Minimum set: inclination sensors; Force sensors, acceleration sensors, Built in actuator displacement, current and temperature sensors
Power	Li-ion batteries, 72 VDC, max. 100 A, 270Wh, 3kg
Operation Features	Networked between distributed control units with independent control strategies and object oriented functional interface fashion

length of walking sequence. Further work may employ different brand or custom made linear electric direct drive motors.

7 CONCLUSIONS

We have proposed and developed a biped robot which key aspects are the anthropomorphism and the use of linear electric direct drive actuation. The robot bears comparable anthropomorphic geometric and mass values to serve further studies and experiments for dynamical walking. Its control structure follows modularity principles with its components functionally distributed but each are completely integrated. The proposed robot design's incremental testing and justification is underway and reached the stage of its complete but preliminary postural balance control. The biped's motion is smooth and silent. Further work shall address the control algorithms which capable to exploit the kinematical advantages of the proposed mechanism.

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