Model Based Control of a Biped Robot

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Abstract: The control scheme of the anthropomorphic biped robot "Johnnie" is based on a comprehensive mechanical model. In order to perform a dynamically stable motion, the robot is equipped with a comprehesive set of sensors that allow to determine the complete state of the system. Since there are still unknown parameters in a real environment, a method is presented to adapt the trajectories in case of major disturbances. A mapping scheme allows to control the orientation of the upper body throughout all phases of the gait pattern. Furthermore, a sophisticated measurement and control of the foot torques has been implemented.

1 Introduction

In the past years, the development of sophisticated biped walking robots has increased rapidly. The reasons for this tendency are the fast improvements in the field of sensors, actuators and computers. Especially the increase of the computational power allows to develop more sophisticated sensor fusion schemes and model based control algorithms that lead to a stable and disturbance tolerant system behaviour of such robots. Key developments have been achieved by [4, 6] who developed powerful biped walking robots.

The goals of this research project are the realization of a biped robot that is able to walk dynamically stable on even and uneven ground and around curves. It is also planned to realize a fast dynamically stable walking motion as well as slow "jogging" with flight phases. The planned gaits have been tested successfully in simulations. Currently, their implementation on the real robot is ongoing. The measured magnitudes are determined by joint position sensors, force sensors and an attitude reference system. The sensors are discussed in detail.

The control of biped walking robots is still a challenging problem. Different groups all over the world are working in this area, but still comprehensive solutions are not yet available. We have developed a general control concept for the biped walking robot "Johnnie", which has been tested in simulations and is now being implemented on a real robot.

Figure 1 shows the assembled robot "Johnnie". It

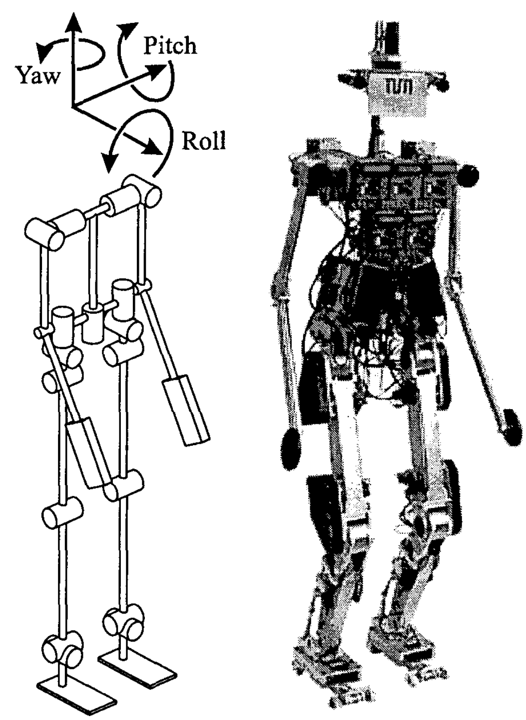

Fig.1: "Johnnie"

is equipped with 17 joints. Each leg is driven with 6 joints, three in the hip, one in the knee and two (pitch and roll) in the ankle. The upper body has one degree of freedom (dof) about the vertical axis of the pelvis. To compensate for the overall moment of momentum, each shoulder incorporates 2 dof. The 6 dof of each leg allow for an arbitrary control of the upper bodie's posture within the workrange of the leg. Such, the major characteristics of human gait can be realized. The robot's geometry corresponds to that of a male human of a body height of 1,8 m [3]. The total weight is about 40 kg. The biped is autonomous to a far extent, solely power supply and currently a part of the computational power is supplied by cables.

2 Sensor System

The sensor system can be subclassified in the internal joint sensors, in force sensors that measure the interaction with the environment and in an attitude sensor system that determines the robot's upper body orientation with respect to the gravity vector.

2.1 Joint Sensors

Each joint is equipped with an incremental encoder (HP 5550) that is attached to the motor shaft. The encoders have two channels with 500 lines and one channel with a reference line. Such an accuracy of 1/2000 of a revolution is obtained using a standard microcontroller hardware. The reference position for the measurement is obtained by light barriers.

2.2 Force Sensors

The interaction of the robot with its environment happens solely with its feet. Hereby, the ground geometry as well as the elastic and frictional properties have to be taken into account. The walking motion is mainly constrained by limitations of this contact situation. Exceeding force and torque limitations of the feet leads to slippage or tilt of the foot. Therefore, it is important to measure and control the ground reaction forces and torques. The biped robot "Johnnie" is equipped with two six-axes force/torque sensors that are integrated in the foot.

The geometry of the sensor has been developed on the basis of detailed simulations. Herefore, the emerging forces and torques acting on the foot for a jogging motion have been determined with a detailed multibody simulation program. Based on these data, a sensor layout has been chosen. Iterations of finite element analysis lead to the final design (Figure 2). The sensor consists of a single aluminum part. Three deformation beams holding strain gauges are within the load path. Two opposing strain gauges operate as a half bridge such compensating for temperature dependence. Thin membranes mechanically decouple the individual beam deflections to a far extent and such reduce cross talk. Special emphasis has been devoted to the strain gauge application. The strain gauges are selected to match the elastic properties of the sensor material. An exact application in combination with an appropriate temperature treatment finally lead to a high zero point stability of the signal.

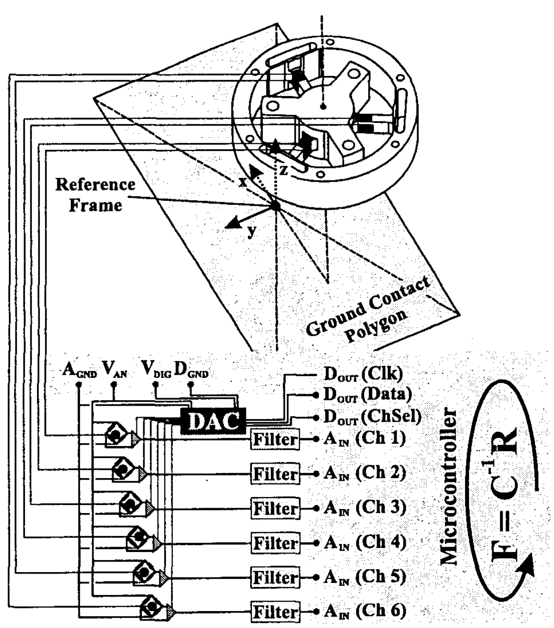

Fig.2: Force Sensor Design

2.3 Attitude Sensor

To allow the robot to walk on uneven ground, it is necessary to measure its orientation with respect to the gravity vector. Therefore, an attitude measurement system is integrated in the upper body. The orientation is determined by a combination of gyros and accelerometers. The acceleration sensors produce erroneous results when the body rotation is superimposed by translational accelerations. On the other hand, integration of the velocity data leads to an unbounded error due to noise and disturbances in the measured gyro signals. To overcome these problems, a variety of sensor fusion methods have been proposed [2, 7]. The scheme that is employed here is based on complementary filtering the gyro- and accelerometer signals. The basic idea is to weight the sensor data in frequency ranges where the respective sensor can be considered as ideal.

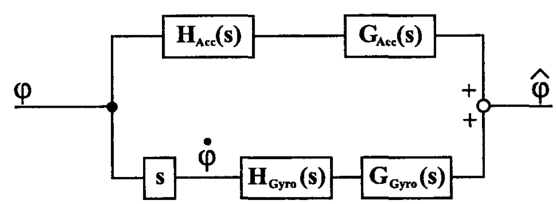

Fig.3: Complementary Filter

Figure 3 shows a block diagram of the filter. H_{Acc} and H_{Gyro} denote the sensor transfer functions, G_{Acc} and G_{Gyro} comprise the respective filter function of the sensor. The condition that the estimate equals the real orientation leads to an infinite number of possible filter functions. As the filter functions are chosen to match the properties of the respective sensor, the sensor transfer functions may be considered as $H_{Acc} = H_{Gyro} = 1$. Like proposed in [1], the velocity is integrated and high-pass filtered. This has the advantage that constant drift is compensated. The orientation computed by the acceleration sensors is low-pass filtered. The time constant of low- and high-pass filter is equal and defines the estimation behaviour. Choosing a low time constant leads to weighting the accelerations high thus making the estimate become sensitive against linear accelerations. Choosing a high time constant allows to take advantage of the good dynamic properties of the gyroscopes. On the other hand, the time-varying bias is not compensated so fast and emerging disturbances decay slower. To reduce electromagnetic disturbances, all sensors and the microcontroller are integrated in a closed sensor housing.

Table 1: Orientation sensor

Gyros	Silicon Sensing Systems	CRS 04
	Bandwidth	85 Hz
	Range	+/-150 deg/s
Accelerometer	Crossbow	CXL02TG3
	Range	+/-2 g

3 Control

For the control of the walking motion, parameters in world coordinates are chosen. To compute these parameters, the apropriate sensor data are selected with respect to a stable walking motion and mapped on the joint angles. In combination with the attitude reference system and a ground reaction torque controller, a transparent system behaviour is achieved. The controlled parameters and their correlation with the sensor data is discussed.

3.1 Constraints

The main difficulties in the control of dynamically walking robots result from constraints that limit the applicability of conventional control concepts. Two groups of constraints need to be considered.

Firstly the workspaces of the joints (1), the maximum rotor velocities (2) and the joint torques (3) are limited.

$$\boldsymbol{q}_{min} \leq \quad \boldsymbol{q} \quad \leq \boldsymbol{q}_{max} \tag{1}$$

$$\dot{\boldsymbol{q}}_{min} \leq \quad \dot{\boldsymbol{q}} \quad \leq \dot{\boldsymbol{q}}_{max} \tag{2}$$

$$\boldsymbol{\lambda}_{min}(\dot{\boldsymbol{q}}, \boldsymbol{T}) \leq \quad \boldsymbol{\lambda} \quad \leq \boldsymbol{\lambda}_{max}(\dot{\boldsymbol{q}}, \boldsymbol{T}) \tag{3}$$

These are typical constraints for industrial robots and can be satisfied by an adequate design and an appropriate choice of the trajectories. However critical control problems result from the second group of constraints that describe the unilateral contact between the feet and the ground. Depending on the normal force $F_{i,z}$ that is transmit from foot $i = 1, 2$ to the ground, the maximum transmissible torques $T_{i,x}$, $T_{i,y}$ and $T_{i,z}$, as well as the tangential forces $F_{i,x}$ and $F_{i,y}$ are very limited.

$$|T_x| \leq 0.5\ F_z l_y \quad |T_y| \leq 0.5\ F_z l_x \quad |T_z| \leq \mu_d F_z \tag{4}$$

$$\sqrt{F_x^2 + F_y^2} \leq \mu_t F_z \qquad F_z \geq 0 \tag{5}$$

While practical experiments show that the robot usually does not start slipping, the limits of the torques in the lateral and frontal direction T_x and T_y lead to a small margin of stability. A lot of research has been spent on concepts to ensure that these constraints are satisfied troughout the entire gait cycle. The "Zero Moment Point" theory is one of the most popular approaches to describe the constraints [10].

3.2 Trajectory Generation

The computation of the reference trajectories is crucial for a stable motion of the robot. In particular the constraints mentioned above have to be satisfied throughout the entire gait cycle. However the trajectories are not uniquely defined by these constraints. An infinte number of trajectories is possible for a given walking speed, such that the most suitable trajectory has to be determined in an optimization. Possible cost functions are the energy consumption, the global stability of the system or aesthetic aspects.

While an optimized trajectory leads to a very good system performance when tracked exactly, it is not necessarily the best solution for a real walking machine. Highly optimized trajectories are usually computed as spline curves in terms of the joint angles. It is very difficult to adapt these trajectories in case of disturbances and to change the gait pattern in an unknown environment. A modification of the trajectories would require a huge data base or an online optimization of the trajectories. Presently both solutions work only in simulations since they require extensive computational power and cannot be used for a system operating in real time.

Biological systems do not track a given set of trajectories extremely exact, but they adapt their motion to upcoming disturbances and can compensate for a great part of sensor errors, inaccurate tracking and disturbances.

We therefore use a reduced model for the computation of dynamically stable reference trajectories. The solution is not completely exact, but it can be computed in real time and allows for an adaptation of the trajectories during walking. This way it becomes possible to compensate model inaccuracies as well as external disturbances.

In the reduced model, it is assumed that the mass of the robot can be lumped to the center of gravity. The motion of the center of gravity in the frontal direction is independent of the motion in the lateral direction. When the center of gravity is kept on a constant height, we obtain a particularly simple solution for the dynamics of the center of gravity. For the lateral direction y_{cog}

the acceleration $\ddot{y}_{cog}$ results to

$$\ddot{y}_{cog} = \frac{g_z}{z_{cog}}(y_{cog} - y_{zmp}) \tag{6}$$

Here g_z is the vertical component of the gravity vector, z_{cog} is the height of the center of gravity and y_{zmp} is the position of the zero moment point. During walking, the center of gravity is shifted periodically from one leg to the other such that the legs can alternately swing forward. During the single support phase the lateral position of the zero moment point shall be constant with respect to the supporting foot. For maximum stability margins it can be selected to be in the middle of the foot area, for minimum lateral deviation of the center of gravity it has to be on the inner edge of the supporting foot. The resulting equations for single support are

$$y_{cog} = c_1 cosh(a(t - t_0)) + c_2 sinh(a(t - t_0)) \tag{7}$$

with $a = \sqrt{\frac{g_z}{z_{cog}}}$. The coefficients c_1 and c_2 are computed such that $y_{cog}(t_0) = y_{cog}(t_1)$ and $\dot{y}_{cog}(t_0) = -\dot{y}_{cog}(t_1)$ with t_0 and t_1 being the beginning and the end of the single support phase. During double support the velocity of the center of gravity shall be constant. The resulting motion of the center of gravity is depicted in figure 4.

The velocity of the center of gravity in walking direction is computed according to the same principle. During the single support phase the zero moment point moves from the rear edge of the supporting foot to the front edge. This way the velocity of the center of gravity can be kept constant while it is above the supporting foot. The corresponding motion of the center of gravity in the frontal direction is depicted in figure 5.

These approximations are not completely exact since the acceleration of the swinging foot does also influence the dynamics of the center of gravity. Practical experiments show that these model inaccuracies can be neglected and compensated by the control of the foot torques. This is possible since the margin of stability is considerably large for an adequate size of the feet.

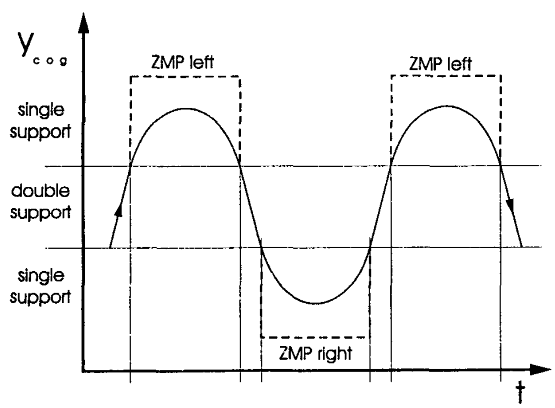

Fig.4: **COG lateral**

3.3 Control of the Trajectories

The described trajectories are defined in terms of the position of the center of gravity, the orientation of the upper body as well as the position and orientation of the swinging foot. When the trajectories are not adapted to the state of the system, they can be transformed into trajectories for the joint angles that are controlled by independent joint controllers. Then only joint angle sensors and tachometers are necessary for the control of the system.

In the practical implementation of this control scheme on "Johnnie" it turned out that even a very slow motion cannot be realized with trajectories that are invariant in terms of the joint angles. This was due to three factors that affect the spacial orientation of the robot:

1. Flexible ground

2. Structural elasticities

3. Steady state error of the controller

While the steady state error can be eleminated by friction and disturbance observers, it is not possible to compensate the structural elasticities of the robot. Furthermore an elasticity of the ground or an inclination of the supporting surface cannot be compensated when only the joint angles are known.

Therefore it is necessary to use an orientation sensor that allows to determine the orientation of the upper body independent of the orientation of the feet. In order to control the orientation of the upper body directly, we give up the control of the trajectories in terms of joint angles, but the orientation of the upper body is controlled directly. Since the orientation of the upper body can only be influenced with the joint torques, the desired motion of the upper body has to be mapped on the joint angles. In the following, the mapping procedure shall be discussed in more detail. A vector of

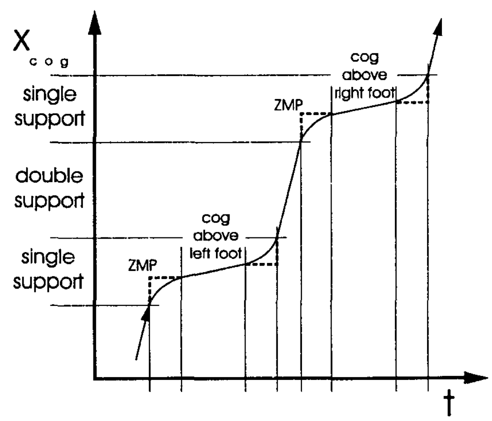

Fig.5: **COG frontal**

controlled variables $\boldsymbol{x}_r$ is chosen, that consists of the orientation of the upper body $\boldsymbol{\varphi}_u$, the position of the center of gravity in world coordinates $\boldsymbol{x}_{cog}$ and the position and orientation of the swinging foot $\boldsymbol{x}_s$, $\boldsymbol{\varphi}_s$. Add to this the angles of the arms $\boldsymbol{\varphi}_a$ and the position of the upper body joint α are included.

$$\boldsymbol{x}_r = (\boldsymbol{x}_{cog}^T \boldsymbol{\varphi}_u^T \boldsymbol{x}_s^T \boldsymbol{\varphi}_s^T \boldsymbol{\varphi}_a^T \alpha)^T \tag{8}$$

This vector contains exactly 17 variables that correspond to the 17 joint angles. These variables have to be mapped on the generalized coordinates, that also contain the joint angles. However the vector of generalized coordintates $\boldsymbol{q} \in \mathbb{R}^{23}$ consists of 23 variables, which are the joint angles and the six rigid body degrees of freedom of the upper body. Therefore additional constraints have to be introduced to allow for a unique mapping of the controlled variables. When the supporting foot is supposed to stand on the ground, we add a set of constraints $\ddot{\boldsymbol{x}}_c = (\ddot{\boldsymbol{x}}_g^T \ddot{\boldsymbol{\varphi}}_g^T)^T = \boldsymbol{0}$ such that the overall system is uniquely defined. Then the combined vector of "constraints" $\boldsymbol{x}$ can be mapped on the generalized coordinates using the Jacobian J:

$$\begin{aligned}
\ddot{\boldsymbol{x}}_r &= \ddot{\boldsymbol{x}}_{ref} + \boldsymbol{D}(\dot{\boldsymbol{x}}_{ref} - \dot{\boldsymbol{x}}) + \boldsymbol{C}(\boldsymbol{x}_{ref} - \boldsymbol{x}) && (9)\\
\ddot{\boldsymbol{x}}_c &= \boldsymbol{0} && (10)\\
\boldsymbol{x} &= (\boldsymbol{x}_r^T \boldsymbol{x}_c^T)^T && (11)\\
\ddot{\boldsymbol{q}} &= \boldsymbol{J}^{-1}(\ddot{\boldsymbol{x}} - \dot{\boldsymbol{J}}\dot{\boldsymbol{q}}) && (12)
\end{aligned}$$

The joint torques can then be determined with the method of feedback linearization, which allows to consider the overall system dynamics. For example for a PD-control the dynamic equations are denoted

$$\boldsymbol{J}\ddot{\boldsymbol{q}} = \ddot{\boldsymbol{x}} + \boldsymbol{D}\Delta\dot{\boldsymbol{x}} + \boldsymbol{C}\Delta\boldsymbol{x} - \dot{\boldsymbol{J}}\dot{\boldsymbol{q}} \tag{13}$$

With abbreviation

$$\boldsymbol{w} = \ddot{\boldsymbol{x}} + \boldsymbol{D}\Delta\dot{\boldsymbol{x}} + \boldsymbol{C}\Delta\boldsymbol{x} - \dot{\boldsymbol{J}}\dot{\boldsymbol{q}} \tag{14}$$

we obtain the equations of motion in standard form:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{W}_1\boldsymbol{\lambda} = \boldsymbol{h} + \boldsymbol{Q}_e \; ; \quad \boldsymbol{J}\ddot{\boldsymbol{q}} + \boldsymbol{w} = \boldsymbol{0} \tag{15}$$

$$\Rightarrow \quad \boldsymbol{\lambda} = (\boldsymbol{J}\boldsymbol{M}^{-1}\boldsymbol{W}_1)^{-1}(\boldsymbol{w} + \boldsymbol{J}\boldsymbol{M}^{-1}(\boldsymbol{h} + \boldsymbol{Q}_e)) \tag{16}$$

The feedback linearization requires intensive computation for the determination of the overall mass matrix and its inverse. Practical experiments show that it is not necessary to consider all of these nonlinear terms for a good system performance. The most important dynamical effects result from the inertia of the motors and gear rotors, which can be considered on a joint basis. The dynamics of the rigid bodies influence the joint accelerations only by the second power of the gear ratios, which are in the order of $\frac{1}{80}$ and $\frac{1}{160}$, respectively. Neglecting these terms saves a lot of computational effort, leading in the end to a higher sampling rate and a higher system bandwidth.

3.4 Foot Dynamics

The mapping procedure allows to control those variables that are actually of interest for the motion of the system. The robot can walk upright on an uneven terrain. However the method does not ensure that the foot torques stay within their limits. For example when the orientation of the upper body deviates slightly from its reference, the foot torques are increased to bring the orientation back to its reference value. Depending on the time constants that were chosen for the tracking of the orientation, the foot torques can easily exceed their maximum limits. The feet would tilt even tough the robot is very close to its reference trajectory. Therefore a direct measurement and control of the foot torques is inevitable when the motion of the robot is based on an orientation sensor.

For our robot it is particularly easy to control the foot torques with a high bandwidth. The torques of the feet depend only on the forces of the ball screw drives that actuate the ankle joint. These are controlled by the same microcontroller that also reads in the data of the six axes force sensor. The controller operates at a sampling rate of $0.4ms$. Steady state errors due to gear friction are compensated by a friction observer.

In order to integrate the foot torque control in the control concept of the overall system, the mapping scheme has to be slightly modified. The two degrees of freedom of the ankle joint of the supporting foot are excluded from the generalized coordinates resulting in a vector $\hat{\boldsymbol{q}} \in \mathbb{R}^{21}$ that has only 21 elements. Correspondingly also two elements of the vector of controlled variables have to be cancelled. These variables will not show the desired tracking performance when the foot torques are exceeded. We choose the position of the center of gravity in the frontal and lateral direction as potentially uncontrolled variables. These are excluded from the mapping procedure, leading to a reduced vector $\hat{\boldsymbol{x}} \in \mathbb{R}^{21}$. Now the remaining controlled variables can still be mapped on the remaining generalized coordintates. In particular the orientation of the upper body can be controlled without any restrictions. Only the position of the center of gravity depends on the foot torques.

The computation of the foot torques is performed with a reduced model that is similar to the lumped mass model that was used for the computation of the reference trajectories. This way the foot torques can be limited such that the feet do not tilt, which will only affect the horizontal motion of the center of gravity. A slight deviation of the center of gravity is not critical for the overall system stability since the reference trajectory can be reached again within the next steps.

The concept to accelerate/decelerate the robot when the upper body tilts forward/backward is known from other papers [4]. However very often it is not quite clear how to compute the acceleration such that the inclination of the upper body is controlled precisely. Using the presented mapping concept, the exact solution results directly from the set of controlled variables.

3.5 Experiments

The presented control scheme has been verified in experiments. Presently stable walking could be realized with up to $1.5 km/h$ and step lengths of $45 cm$. A crucial point for the performance of the presented control scheme is the accuracy and the crossover frequency of the employed sensors. In particular the orientation sensor and the force sensors are very critical. Right now we have implemented a new orientation sensor which will allow for a faster walking pattern.

Another crucial point of the mapping scheme is the computational power. Since the orientation of the upper body depends on the entire system, the mapping of the vector of controlled variables on the generalized coordinates can only be performed on a central CPU. It is not possible to control the trajectories on independent joint controllers that operate in parallel. However this problem is solved with the powerful PC-units that are commercially available.

3.6 Fast Walking

The design of the machine and the control concept was developed for fast walking including short air phases. This motion was verified in simulations, which could proof the stability of a jogging motion in a pure 3D-multibody simulation. Since disturbances are mapped on the horizontal velocity of the center of gravity, the overall system stablity is not affected. During fast walking, the velocity of the center of gravity is the controlled by an adaption of the step length of subsequent steps. This way the robot can be controlled even in the case of major disturbances.

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