A foot following locomotion device with force feedback capabilities

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Abstract. *This paper deals with the design of a locomotion device which enables the user to walk naturally in any desired direction. The user stays in place while walking due to the recentering control which compensates all movements originating from the walker's movements. Moreover, the walking area is not limited in any direction. Spontaneous turns up to 90 degrees can be managed without restrictions; slower turns can be carried out with infinite angles. Different from existing 2D foot followers, this device can realize free movement of the walker in any direction by new rotational degrees of freedom. The device can be additionally equipped with a force feedback system to increase immersion.*

Additional Keywords: 2D locomotion interface, walking in VR, full motion interface, force feedback capability

1 INTRODUCTION

Many attempts have been made to enable a human being to walk infinitely in virtual reality environments without any limitations. Different solutions were provided. The Patent US006152854A [1] described many basic actuation principles of possible solutions. At the beginning, metaphors were used such as pedals in the Sarcos Uniport (Sarcos Systems). The need for a more spontaneous and natural movement which is closer to human gait lead to the development of systems as the Torus Treadmill [2] and the Circula Floor [3] which were presented by Iwata. Both faced problems with consistent or sufficient speed. The Gait Master [4] and HapticWalker [5] offer linear gait trajectories while the footpads are virtually attached to the walker's foot. The "Sensorial and driving locomotion interface" [6] had the same goal but compared to other solutions the footpads stay on the floor and do not follow the foot on the vertical axis. Within the group of the foot-following systems, it is

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obviously very challenging to achieve changes in directions such as walking in curves or steep turns.

Our contribution presented in this paper is a locomotion device which overcomes the limitations of nowadays foot-following platforms concerning direction and walking speed and adds elementary functions to provide natural gait in any desired direction. The walker on the device is able to perform virtually any natural movement without using metaphors. He or she is not limited in distance and can change the direction at any time.

First, this paper will describe the mechanical system and the issues related to the construction. In the second part, the basic tracking and control strategies will be outlined. Finally, a force feedback extension is presented.

2 DESIGN

The platform consits (figure 1) of two arms which carry a footpad that always remains underneath the walker's foot. Each arm has 3+1 DOF. The footpad is connected to the arm with a rotational degree of freedom (1). The arm is designed for linear motion (2) and can be rotated (3) at the carriage mounting. Another degree of freedom (4) is necessary to achieve a completely free motion and to avoid collisions of the pads. This enables the carriage to rotate infinitely around the platform.

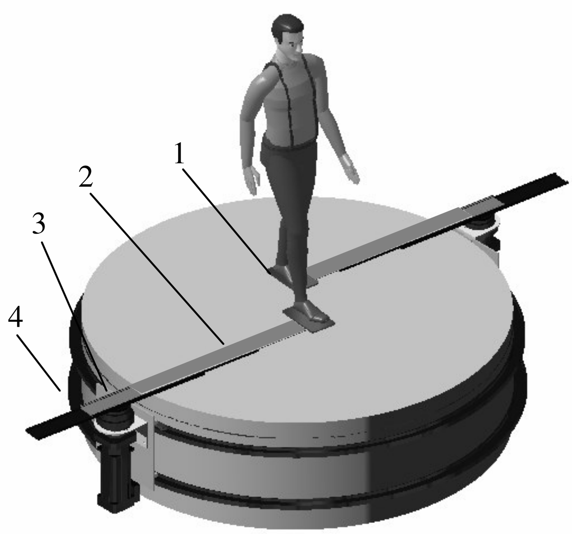

Figure 1. Design of a foot-following platform with infinite rotation abilities

Each footpad is thus able to cover a large area on the platform as shown in figure 2. It is limited by the working range of the telescopic linear guide.

Arm 1 (red, left) and arm 2 (blue, right) have two circular ranges of operation. With respect to the minimal extension which limits the maximum range of the opposite system a rhomboid shaped walking area (figure 2) can be achieved which is constricted near the

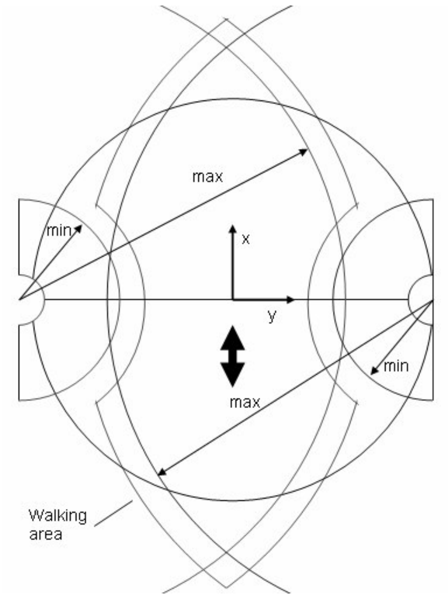

Figure 2. Walking Area

carriages (line labeled “walking area”). The narrower center strongly depends on the length ratio which is defined by the mounting position of the linear telescopic arm. If mounted at the outer end, the disturbance of the walking area is too high and undesired allocation of masses lower the efficiency. Mounting the inner end enhances the allocation of mass and averts the necking of the walking area. But in this case, the reach of the telescopic guide has to be very high which results in more segments. Moreover, the clearance tends to increase and stability decreases as the guide cannot be stabilized. An optimal ratio has to be chosen depending on the size.

For the described platform which has a diameter of 2500 mm, a telescopic guide with 3 parts (2 moving segments) was chosen. It has a retracted length of 1216 mm and is mounted at 750mm from the outer edge, which means that the walking area will be constrained in a circular area of 466mm around the center of rotation. The maximum length of the guide is 2500mm which corresponds to the diameter of the platform. The full length will not be available due to restrictions which derive from the construction of the guide: The rotation in joint (3) generates high lateral acceleration forces which require both high stiffness and small masses. By limiting the maximum reach, the leverage within the telescopic gear is also reduced.

The telescopic gear is actuated by a combination of gear racks which provide a synchronous deployment of both segments. Alternative constructions with higher dynamics such as a direct linear drive have been evaluated. The gear rack is on the one hand a very solid and simple technology which can be carried out with a small overall mass and little maintenance at very reasonable cost. Moreover, the motor itself can be mounted on the carriage and force can be transduced via the rotational joint (figure 1, pos. 4). On the other hand dynamics and clearance degrade speed and accuracy. The linear direct drive is able to move very precisely at good dynamic behavior. But these characteristics are costly: This drive is not only very expensive, the overall mass of the arm (and by that mass inertia) increases dramatically. Finally, maintenance and robustness against hostile objects (elements potentially falling from walkers as cloth, coins, dust) in combination with high magnetic fields are weak points of a linear direct drive in this context and thus not applicable.

The vertical force which is applied by the walker stepping on the footpad is not only absorbed by the telescopic guide but also by support bearings which slide on the platform surface. The angle of the footpad is adjusted with a small motor with bevel gear. The overall height offset of the footpad above the platform remains small.

The carriage can rotate the whole arm around the platform. The effects of this arrangement will be described in detail in the following chapter.

The projected cost for the overall assembly is 80.000 Euros. The most costly single component within is the linear telescopic guide (2) due to its high precision and stability recommendations. The planetary drives (3) are also relatively expensive but available as serial models. All components are projected to provide long term operation with low maintenance. Greasing and basic inspection is recommended every 100 hours of operation, a full service is needed after 500 hours. The overall lifetime without exchanging core components is projected to exceed 2000 hours.

3 MOTION

When walking on a straight line, the footpad is positioned using systems (1), (2) and (3) shown in figure 1. As soon as the walker changes his direction, the advantage of this design becomes clear. For example the walker decides to walk a curve. First, the foot which is swinging forward, turns and indicates the new direction. Due to the low inertia of (1) and (2) the footpads can easily follow the foot. In the next step, the walker's centre of mass also starts to change its direction. The carriage starts to turn the whole system and tries to stay in a lateral position to the walker. A concept of control will be described in section 5.

By implementing this system, a very quick response to the walker's movements is possible because the directly concerned parts are of little weight and can react quickly. To avoid collisions and blocking of the system, the carriage will only respond to changes of the global direction. The movement of (4) is slower because of the higher masses but can be improved by using actuators with a higher power density. This can easily be done because of the fact that neither mass nor size matter too much at this point of the construction. Finally, the carriages will always tend to remain at the two opposite points on the circle for best coverage.

When walking, the mechanical system is designed in such way that the adjacent possible, next step is within the optimum reach of the footpads. The system is also able to handle uncommon situations such as 90 degree turns or sidesteps.

4 TRACKING AND SECURITY

The position of the walkers feet has to be retrieved precisely. This can be done by commercially available tracking systems as ART or VICON for example. Heel and toe are equipped with markers as well as the hip, which is in our case concerned to be the centre of the body mass. Shoulders could be taken as well; the question which point will be more robust for direction prediction is subject of further research and not critical at this point. The hip provides the orientation of the body and the eccentricity of the walker. The challenge is to attach markers to the walker in a way that are not covered through the moving hands. Precision of the tracking has to be ensured with reasonable amount of cameras. Heel and toe markers provide the orientation and the position of the foot. The control needs to distinguish between two states: Foot on the platform and foot above the platform. The detection of the states with the tracking system only will not be very stable. A combination of a 6DOF torque sensor within the footplate proves to give better results. This sensor is needed anyway in a further step to control the foot forces.

To get better results, the tracking should moreover distinguish between two states of contact with the platform: Foot landing on the platform but not yet fully placed and full contact. The same procedure is valid in reverse order for the foot loosing contact with the platform. The contact state can be determined from the angle between the heel-toe-line and the horizontal line as well as from the mass detected by the sensor. The differentiation is very important for the controller's design because the tranferable forces are different.

The acquisition rate of the tracking system has to be quite high. ART manages 60 Hz which is at the lower end for this application. The VICON System provides frame rates from 1 to 10 kHz which is better but also more expensive.

Security issues are of great relevance when looking at the design principle of our platform. Big momentums and velocities can produce huge shear forces if any object is stuck between moving parts. To prevent damage or injury, several redundant measures have to be taken to ensure safe operation.

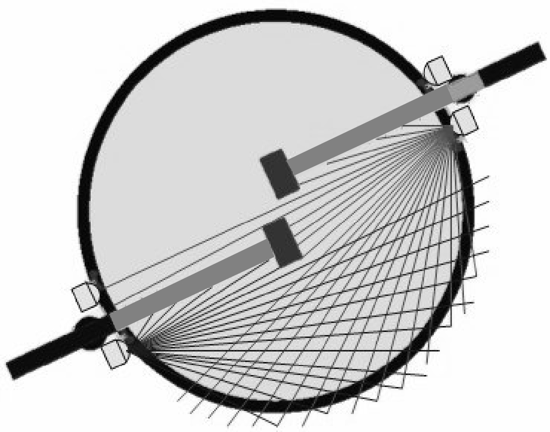

Figure 3. Safety laser scanners covering the whole area at any time (beams only shown for two scanners)

First, the tracking system provides exact positions of the important body parts. The positions of the mechanical components are known due to sensor measurements. If the security system recognizes any lager deviation between actual and reference position (i.e. the footplate can or does not follow the foot), the system will be shut down. Moreover, the footplates have a certain offset from the platform's surface (>10 cm). If the user misses the footpad and steps on the platform, the tracking system will deliver vertical positions which are below a certain secure barrier. The security system will then subsequently shut down the system.

Second, as the tracking system may not be accurate at any time due to coverage or failure, a more hardware based and reliable system is needed. A system of safety laser scanners can provide complete coverage of the whole platform area. Figure 3 shows the mounting of four units and the coverage of two scanners on one side of the footpads. The actual arm positions can be derived from sensor information and the mechanical model. As soon as an obstacle is detected by the laser scanner changes and the security system can shut down the platform.

Finally, a system can be implemented which generates velocity-sensitive areas of protection. When the walker is moving at full speed, the footpads pass each other with a quite high velocity. The potential shear force between the pads is enormous. It must be the goal to widen up the gap to prevent an obstacle from being smashed between the pads. This can be done with the area of protection mentioned above. The faster a footpad moves, the bigger the area of protection becomes. On its sides, the protection area is at least the maximum size of a potential obstacle (e.g. foot). In the direction of motion, it's a zone which is needed in case of an emergency stop to break the mechanism plus the obstacle size. On the back side of motion no protection zone is needed because the inertia will save the obstacle. The control has to take care of the protected areas. This means that a pad which follows the foot without direct contact may leave the position directly underneath the foot to respect the security area. Figure 4 shows the influence on the trajectory of such a strategy.

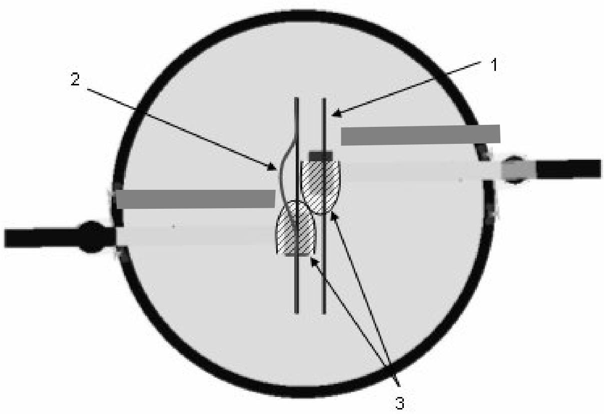

Figure 4. Normal footpad trajectory (1) and adapted line (2) with respect to security areas (3)

The straight lines (1) show the setpoint tracking of a linear foot motion (simplified for demonstration). The foot has contact with the right footpad and is moving towards the bottom of the image. The left foot is swinging upwards and the left footpad tries to follow. When both footpads move, they are protected by a security area (3). Thus, the control changes the trajectory of the left footpad resulting in (2).

This concept proves to be very effective: as long as the foot moves with high velocity, the walker will not set it on the ground because this would cause him to fall (actually). To place the foot, the relative speed towards the ground has to become zero. So there is enough time for the footpad to get into its position while the foot decelerates, even if it has been moved away from the foot in a high speed phase.

5 CONTROLLING THE PLATFORM

To control the platform, all of the above mentioned sensor and tracking data mentioned above is required.

The Tracking can be divided into four logical sectors: The hip tracking for the general orientation of the platform arms. The foot tracking and force measurement which deliver data for the high speed positioning. The joint sensor data which are used to setup the internal mechanical model to provide accurate control. And finally the environmental restrictions which limit the forces on the structure as well as on the walker.

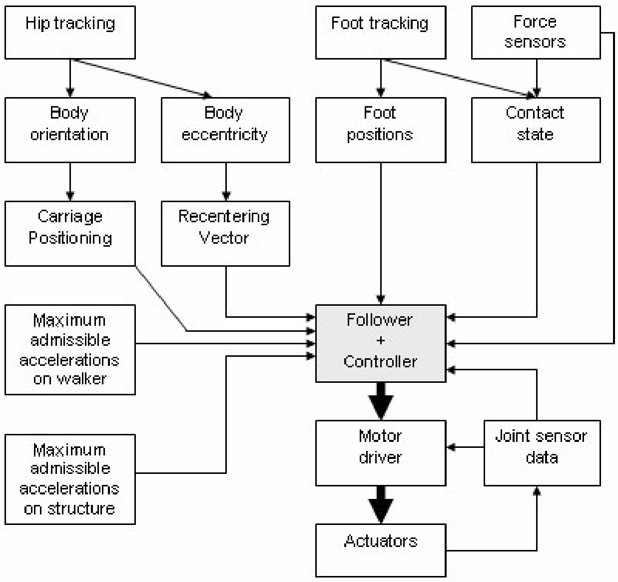

Figure 5. Control Scheme of the Platform

At the beginning of a session the walker steps on the footpads. The control executes a slow initialization routine (moves the walker) to calibrate the sensor and tracking information. Moreover, the weight is stored for further calculations to determine if the foot has full contact on the footplate.

Then the subject starts to walk. At first, the centre of mass (hip) will leave the centre of the platform while the foot pads follow the foot movement. After a certain “dead zone” of the hip position, the control starts to add a recentering component to the movement of the footpad which has full contact to the foot. The resulting acceleration on the walker's body are limited to values the user's perception does not recognize. The research of these optimal acceleration values is the subject matter of our project partners.

As soon as the subject starts to walk a curve, the carriages will start to turn. Although they can move independently, the control will try to keep them in a most opposite position for best coverage of the whole area. The movement of the carriages changes the mechanical constraints of the system. The arms are moved accordingly to compensate the movement of the carriages. For example; the user stands still and performs a 90 degree turn. The footpads can easily follow the foot as the movements are quite small. But the walker's orientation has changed largely. The carriages will start to perform the same 90 degree turn but due to dynamic limitations they will take longer to react. They will rotate around the platform right after the user's turn and the joints (1), (2) and (3) in figure 1 will compensate the movement. The walker will not be aware of the compensation.

As soon as a direct contact between foot and platform is detected, the control waits until the force sensor and tracking data recognize a full contact. Now, the forces applied by the foot are measured additionally. With respect to the velocity and direction of the centre of mass the movement of the foot is compensated. The walker shall not have the feeling to slip away as walking on ice, but feel considerable counterforce. The pad under the foot with full contact will maintain its direction while velocity is controlled. The orientation is fixed from the moment the foot steps on the pad, the footpad behaves like the passing floor in reality.

This means that at the beginning the walker will first move away from the, then return to the centre because of the recentering control. This can be improved by using a force feedback system which will be described later.

A mathematical simulation has been built to evaluate the principle. This model only uses the tracking data to carry out platform control. The force sensor distinguishes between full contact and no contact / loose contact. The carriages stay at a most opposite position. Tracking data for straight and curved walking has been used for calculation as well as a 90 degree turn. Yet force sensors have not been used for motion control to evaluate the

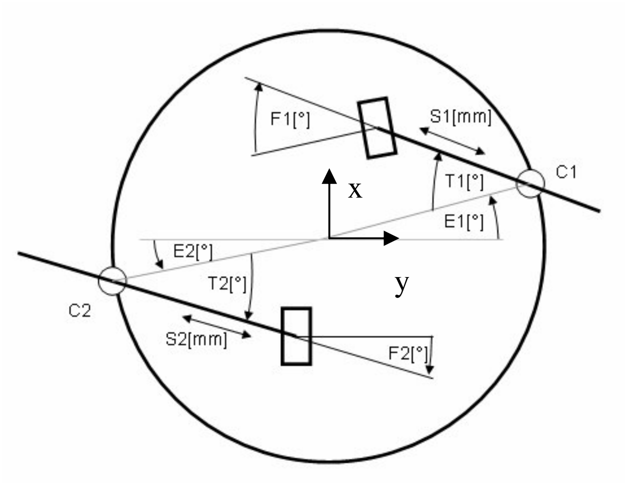

Figure 6. Conventions

efficiency of tracking; they can be added after further research with regard to the results found in this simulation. The real-floor input data was compensated by the recentering portion of the platform to get the virtual tracking points. Figure 6 shows the conventions used in the displayed results. The variables (E, T, C, S, F) are identical to the effective motion of the actuators. Thus, it is possible to use the results for the dimensioning of the mechanical components directly.

The control is set up as shown in figure 7. The setup is able to use tracking data which is recorded on solid ground. As mentioned, a compensation is implemented which corrects the input values by subtracting the recentered proportion.

Four functional arrays can be found. The first one is used to control the carriages, what will be treated later. The second one analyzes the hip coordinates and determines the recentering acceleration which is limited due to the described perceptual limits. The other two arrays manage the positioning of the footpads. The detection of the contact state of the feet is very important. If there is no contact, the pad follows the foot. As soon as a complete

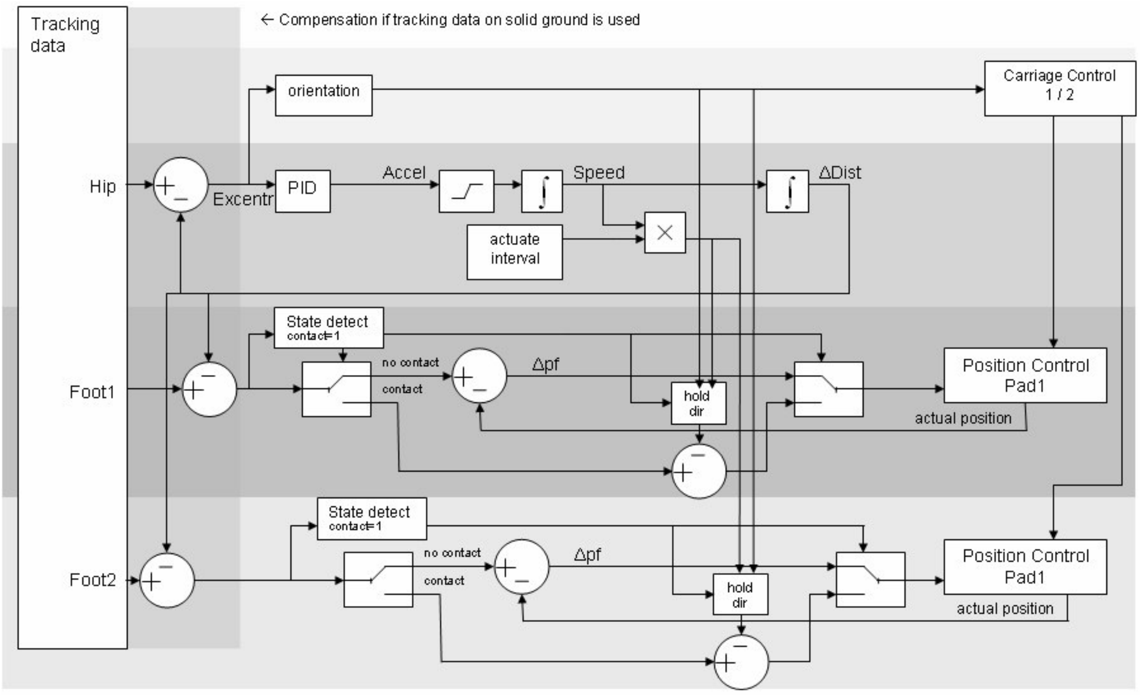

Figure 7. Control setup for unrestricted omni directional walking

contact is established, the controller switches over to the contact-mode which applies the walking speed to the foot. This speed is locked to prevent a hip-turn to irritate the foot's trajectory. For compensation of the (solid ground-) input data, the recentered distance is looped back to the input. The loop back on the real platform is realized via the tracking system. An additional dead zone can be implemented to avoid instability at the near centre. This can easily be implemented by adding a dead zone function after the eccentricity value in the hip control. The hip control generates a speed value which is the virtual walking speed. This speed is the same as the foot would recognize on real ground, when it is in contact state. The control manipulates the actual foot position for every time segment. Due to the constant frame rate of the tracker, the time segment between each calculation step is known. Thus we can exactly determine the desired position and speed of the footpads. This generates a smooth movement which is – from the walker's view - almost like running on a conveyor belt. The Control boxes labeled with "Position Pad 1 / 2" and "Carriage 1 / 2" are independent controllers for the positioning of the elements (actors). All controllers are driven in a positioning mode with speed information control.

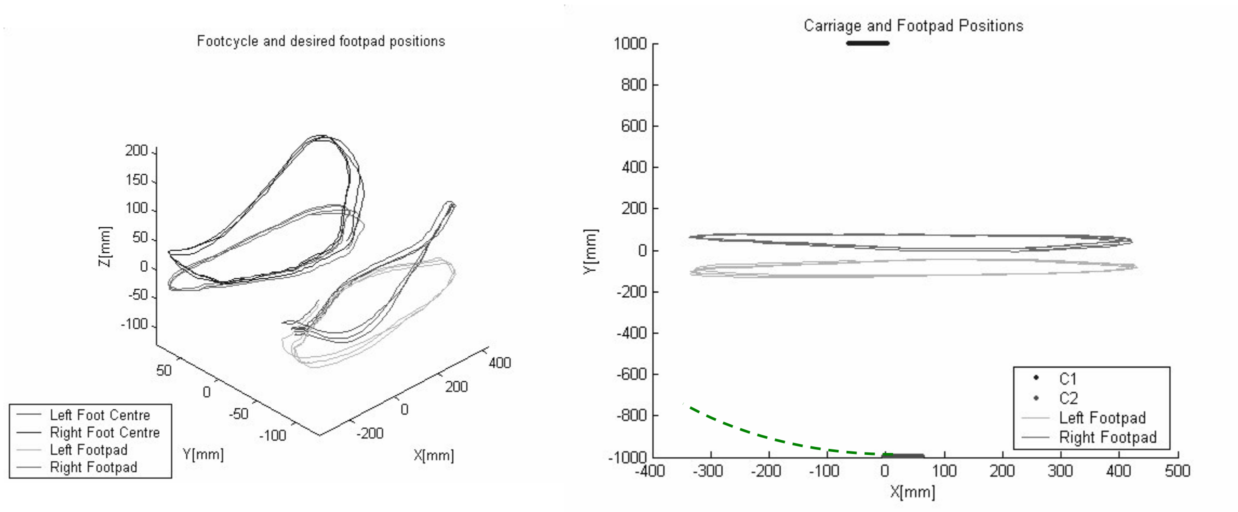

Figure 8. Gait trajectories and desired footpad motions

At first, let's have a look at the reactions of straight walking in a steady state.

The left side of Figure 8 shows the compensated gait trajectories of two feet with the desired footpad motion in a simulation model of an omnidirectional device. The world coordinate system is displayed in the diagram. It can clearly be seen that the foot maintains its direction with respect to the world coordinate system as soon as it is placed on the floor. This behavior is also valid for curved walking trajectories, in this case – in reference to the walker's coordinate system, the foot performs a curved trajectory which is the inverse of the walker's motion trajectory.

With regard to the platform, the pathway of the stance foot is always linear. This is obvious when we look at different motions. When walking a curve, the centre of body mass describes the motion pretty well. When a foot is placed on solid ground, the person expects that the floor underneath performs motion as expected in the real word which means that the floor maintains the walking speed. In our case, walking speed exists only virtually. In a linear case, the floor moves also on a linear pathway as mentioned. When the curve starts, the user's turning adds the curved proportion to the linear footmotion which is perceived by the user's coordinate system due to the change of orientation and his decentering movement. Nevertheless, the platform must still move the foot in a linear way in the inertial coordinate system. As described, the user will move out of the center during a turn and the control will subsequently add a recentering component in x and y direction.

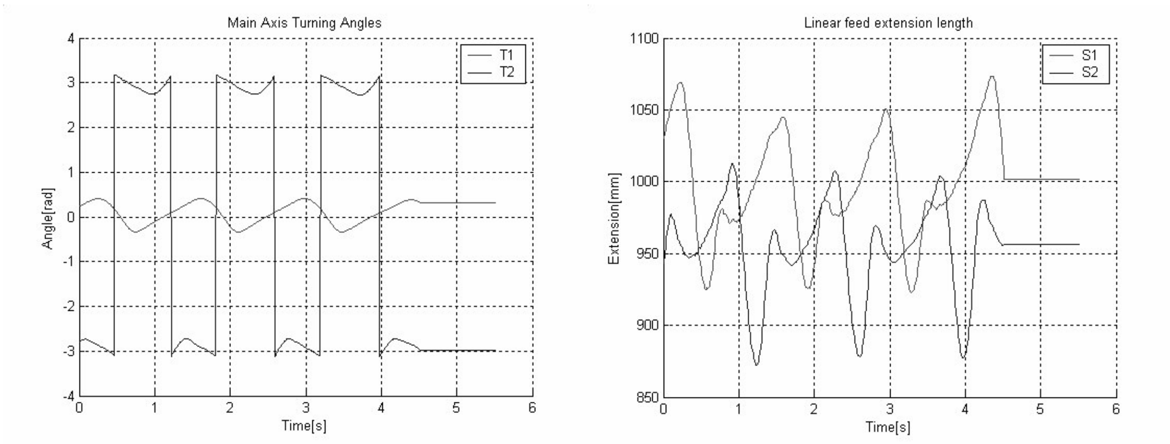

Figure 9. Movement of the actuators and resulting motion

The carriage and footpad positions are displayed on the right side of Figure 8 assuming a 2000mm diameter platform model. Please note the different scaling of X and Y for better visibility. The carriages (C1, C2) stay in a lateral position to the walker as expected. The dotted line (which would form a circle if continued) shows the way of carriage C2 in case of a turning walker. The joint movements of the classic 2D actuators can be found in Figure 9. The linear feed (S1/S2) in combination with the main axis (T1/T2) produces linear motion. The footpad (F1/F2) turns accordingly and is not displayed here. The linear continued motion can be seen in the upper diagram: As soon as full contact is established, the trajectory becomes linear.

6 FORCE FEEDBACK EXTENSION

The design of the platform is very flexible and allows several extensions. One of them is the implementation of a force feedback system as shown in figure 10. The recentering accelerations on the walker's body are limited and allow fast recentering. Thus big scale platforms are needed to provide a natural gait feeling. With the application of a force feedback system as described by Christensen, Hollerbach et al.[7], but for 2D, the platform usability can be increased.

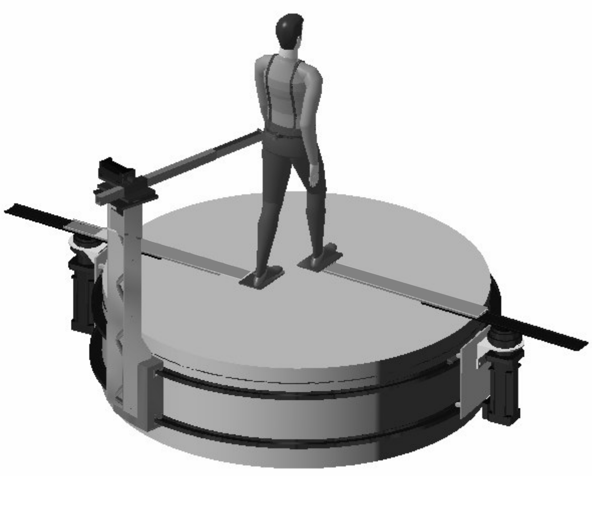

Figure 11. Force feedback assembly

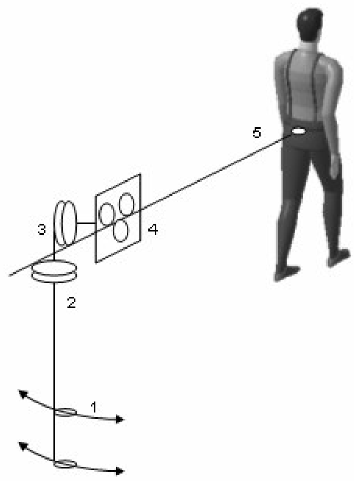

Figure 10. Reduced mechanical model

Figure 11 shows a reduced mechanical model for the force feedback apparatus which has three controlled and one loose joints. The carriage (1) may move around the platform as described for the footpad systems. On top of the carriage a rotating assembly (2) can be found. An actuated bar provides linear action (4) and may turn freely in joint (3) to compensate the body size of the walker and the vertical motion during gait. At the end of the bar the walker is attached through a flexible joint (5). The force which is applied to the body is allocated by a special vest. This setup is able to apply forces in two dimensions. With that technique it is possible to reduce significantly the size of the platform because the acceleration limitations on the body of the walker do not influence the decentering any more. From the first moment on the walker can be kept in the centre.

7 CONCLUSION

The principle and control strategy of this new device was evaluated by numerical methods and was found very proving. It was outlined that, using the described principles, the platform always tends to cover the area of the adjacent next step in an ideal way. For the design of the platform, the construction of some sophisticated elements is necessary to meet the extreme recommendations concerning mass and stiffness which are required by the mechanism. The main issue of the platform is to ensure security by preventing shear forces and impacts of any kind. A combination of both software and hardware based systems grants secure operation.

To increase security, an additional impedance control [8] can be implemented by using force and torque sensors in the joints and an adapted control strategy.

Further improvement can be accomplished by introducing the force sensor into the control strategy. The implementation of the force feedback carriage is the key to a small scale platform with a highly immersive experience for the user.

Further work will include the implementation of the system into a fully immersive environment using a head mounted device. The impression of natural walking will be evaluated using the research results about recognition and haptic feedback which will be done by our project partner MPI for Biological Cybernetics in Tübingen.

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