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A Control Assist Suit for Stable Walking

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***Abstract*— We propose a wearable active suit that assists human motion control rather than providing power. The suit includes motion sensors, a whole-body motion controller, and actuators that trigger human motions according to orders from the controller. The controller is implemented based on a passive walking model to examine the concept of the motion control assistance.**

I. Introduction

Exoskeleton suits have been developed and used for instantaneously assisting human motions and promoting rehabilitation as a long-term effect [1, 2, 3]. These suits use joint angle sensors or EMG analysis to predict intended user movements and to provide powered assistance for the predicted movements. The benefits of these suits for instantaneously assisting movement have been evaluated mainly according to metabolic consumption with and without them. These suits provide power for movement, while the users control whole-body motions. In this sense, we can call these suits *power assist suits*.

Central nervous system disorders due to disease or aging can make voluntary actions unstable and difficult to control, making it desirable for an exoskeleton device to assist control of coordinated motions rather than providing power assistance. We thus considered the concept of a *control assist suit*, that is, a suit that assists control of whole-body motions. This concept was inspired by gait improvement via rhythmic auditory stimulation for stroke and Parkinson's disease patients. Auditory stimulation can provide a desired rhythm, and the suit can additionally specify which muscle to move [4, 5].

A control assist suit does not provide power for motions. Rather, it tries to trigger motions through orders from a cybernetic motor nerve system. In that sense, a human brain and a cybernetic controller can be considered as a hybrid control system for human motions. Because control assist does not have large power demands, we can use a compact actuator to drive it. It is thus reasonable to implement control assist as a wearable suit rather than as a soft exosuit or other mechanical exoskeleton [6].

The remainder of this paper is organized as follows: Section II proposes the concept of a control assist suit and provides detail of a prototype. Section III describes implementation examples of the cybernetic controller based on passive walk theory and contact wrench control. Section IV presents experimental results using the prototype and the cybernetic controller. Section V concludes the paper.

II. CONCEPT OF A CONTROL ASSIST SUIT

A. Control Assist

Figure 1 shows the concept of control assist suit. When the central nervous system sends a motor command to a muscle, the resulting motion provides feedback to the central nervous system via sensory nerves for control. A control assist suit simultaneously senses the human motions, and a cybernetic motion controller finds a desirable motion for stabilizing whole-body motion. Suit actuators then provide triggers to muscles to generate the desired motions, these triggers are detected by sensory nerves, and feedback is supplied to the central nervous system. In other words, the suit tries to form a cybernetic feedback loop supplementing the nerve loop.

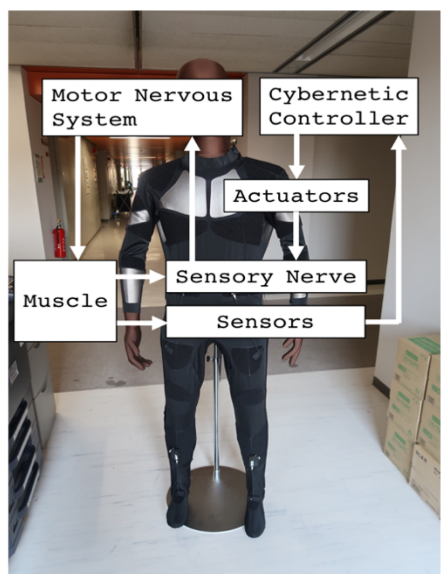

Fig. 1 Concept of control assist suit

A power assist suit uses a sensor, EMG sensor for example, to identify voluntary user movement [1] and control the assist power to achieve controller movement. A power assist suit can thus be considered a special type of a control assist suit. Challenges for such suits include examining the reaction of the central nervous system when it receives triggers from the cybernetic controller that is supposed to stabilize motion, and experimentally evaluating them.

B. Control Assist Suit Prototype

We developed a prototype of control assist suit (Fig. 2) to examine its practicality. The suit utilizes linear actuators (D7-6PT-3; Mighty Zap), IMU-based leg orientation sensors (SEN-13762; SparkFun Electronics) (Fig. 3), a controller, and a battery mounted on a wetsuit. The linear actuators pull wires to trigger joint muscle motions. Conventional soft exoskeleton suits use rotary motors and thread winding mechanisms to pull wires [6], but these wires can become loose or tangled. The wires of control assist suit do not need to be pulled far, because they only trigger motions, allowing the use of linear actuators instead of motors and thread winding.

Mounted actuators bend and extend the hip and ankle joints. The degrees of freedom are chosen to stabilize the walking motions of a frail elderly person. The linear actuator can pull the wire up to 30 mm with 0.1-mm control accuracy. Orientation sensors mounted on the lower legs measure orientation from the upright state. The wetsuit fabric is strengthened to minimize sliding when pulled by the wire. The controller reads joint angles via IC^2, identifies stable motions, and outputs commands to the linear actuators via RS-485 using a USB interface board (IR-USB01). The battery can be used for about two hours.

Fig. 2 Control assist suit prototype

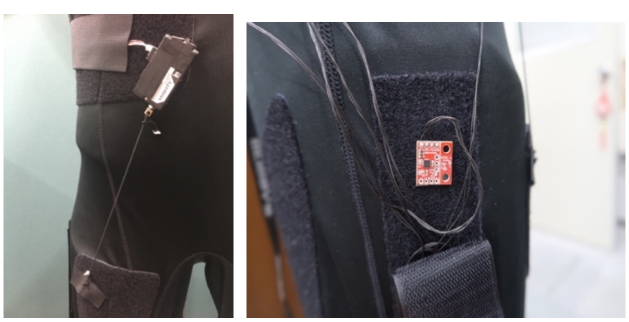

Fig. 3 Linear actuator and joint sensor

Dynamic actuator characteristics such as power, travel distance, and speed must be evaluated for the actuator to trigger suit motions. Figure 4 shows actuator responses at the maximum speed; the upper graph shows contraction and the lower graph shows extension. The red line shows the position of the actuator head and the blue line shows its velocity. This data can be sampled at minimum intervals of 151 msec, but the graphs show 200 msec intervals for clarity. The actuator movements were proven to be sufficiently strong and fast for users to feel motion triggers.

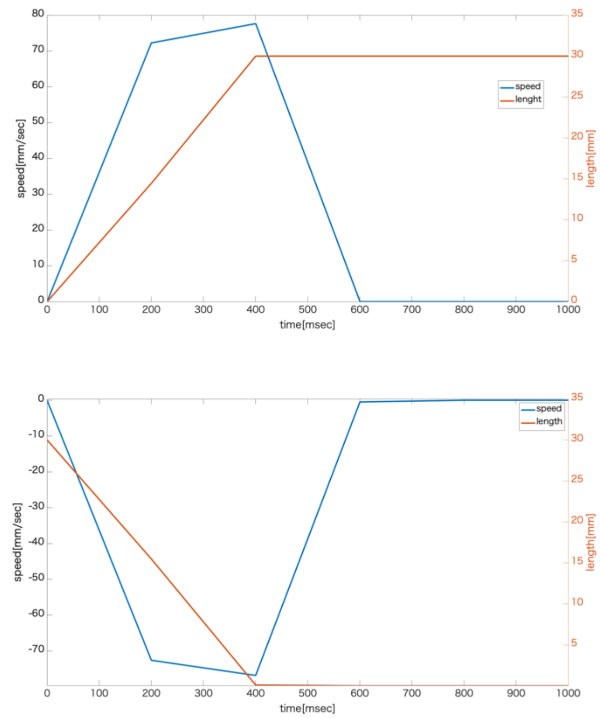

Fig. 4 Responses of linear actuator

Figure 5 shows examples of data measured by the leg orientation sensors.

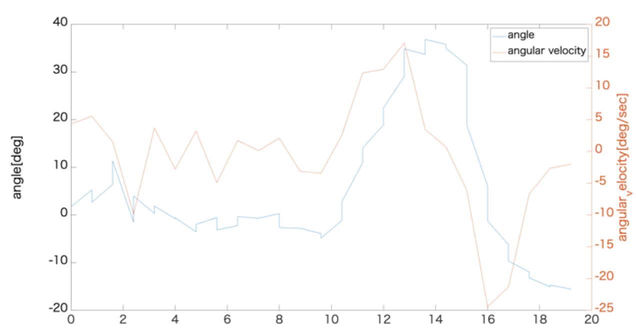

Fig. 5 Examples of orientation sensor data

III. CYBERNETIC CONTROLLER

Various cybernetic controllers can be considered depending on the goals for motion assistance, such as power efficiency, stability of walking, or other motions. Stability can be evaluated according to steady-state robustness or by a contact stability criterion like zero moment point (ZMP). We propose two types of cybernetic controller as follows:

A. *Virtual Passive Walk*

Passive walk has been intensively investigated to explore efficient and natural walking [7, 8, 9, 10, 11]. The following describes a compass-like biped model.

The equations of motion for the compass-like model can be expressed as

$$I(\Theta)\ddot{\Theta} + C\big(\Theta,\dot{\Theta}\big)\dot{\Theta} + g(\Theta) = Su, \quad (1)$$

where $I\big(\ddot{\Theta}\big)$ is the inertia matrix, the matrix $C\big(\Theta,\dot{\Theta}\big)$ for centrifugal force, $\dot{\Theta}^T = (\theta_1 \quad \theta_2)$, $g(\Theta)$he grabity force and Su the input torques at a hip joint and ankle joint, and given by

$$I(\Theta) = \begin{pmatrix} m_H l^2 + ma^2 + ml^2 & -mbl\cos(\theta_1-\theta_2) \\ -mbl\cos(\theta_1-\theta_2) & mb^2 \end{pmatrix},$$

$$C\big(\Theta,\dot{\Theta}\big) = \begin{pmatrix} 0 & -mbl\sin(\theta_1-\theta_2)\dot{\theta}_2 \\ mbl\sin(\theta_1-\theta_2)\dot{\theta}_1 & 0 \end{pmatrix},$$

$$g(\Theta) = \begin{pmatrix} -(m_H l + ma + ml)\sin\theta_1 \\ mb\sin\theta_2 \end{pmatrix} g,$$

$$Su = \begin{pmatrix} 1 & 1 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} u_1 \\ u_2 \end{pmatrix}. \quad (2)$$

See Fig. 6 for definitions of the parameters

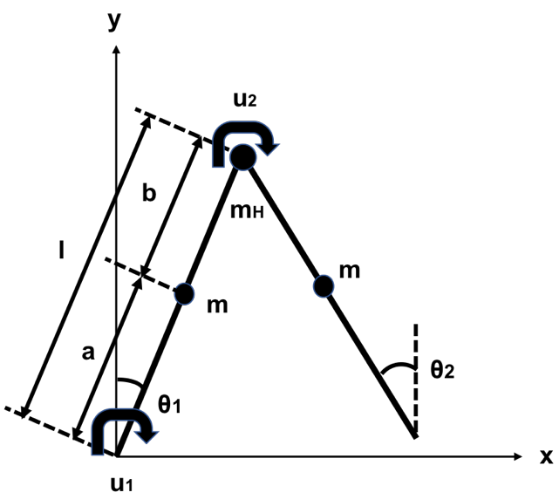

Fig. 6 Model of a compass-like biped

Joint torques in the virtual passive walk can then be controlled by solving

$$\dot{\theta}_1 u_1 + (\dot{\theta}_1 - \dot{\theta}_2)\, u_2 = Mg\tan\phi\dot{X}_g - \zeta(E - Mg\tan\phi X_g) \quad (3)$$

where M is the total mass of the biped, ϕ the angle of the virtual slope, X_g the center of the mass, ζ a feedback gain, and E the total energy given by

$$X_g = \frac{1}{M}\left((m_H l + ma + ml)\sin\theta_1 - mb\sin\theta_2\right),$$

$$E = \frac{1}{2}\dot{\Theta}^T I\dot{\Theta} + P,$$

$$P = \left((m_H l + ma + ml)\cos\theta_1 - mb\cos\theta_2\right)g. \quad (4)$$

This is a simple model with only two degrees of freedom, but it is sufficient for the prototype of control assist suit that has only a few degrees of freedom. Feedback control by Eq. (3) should produce walking in a steady state that is a limit cycle of the dynamics system. Section IV presents experimental results using this system.

B. *Contact Wrench Control*

Another stability criterion for biped walking is contact stability including the ZMP of the suit user, or contact wrench sum (CWS) in the general case where the user is, for example, walking over rough terrain or grasping a handrail [11]. The speed of convergence to the limit cycle can be used for evaluating the walking rhythm, and the contact stability criterion realizes dynamic balance during motion. The following describes a cybernetic controller based on CWS.The model of the user of the suit is shown in Fig.7. Let $v_{H1}, v_{H2}, v_{F1}, v_{F2}, v_B$ be the velocity of the right hand, left hand, right foot, left foot and the waist respectively, and $\omega_{H1}, \omega_{H2}, \omega_{F1,}\omega_{F2}, \omega_B$ be the angular velocity of them respectively. is the position of the center of the mass , and are the momentum of the user and the angular momentum with respect to X_g.

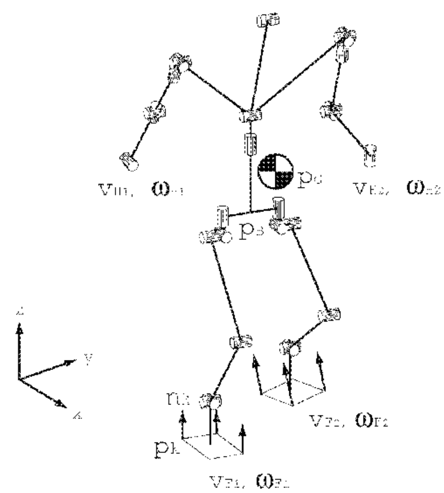

Fig. 7 Model of the suit user

A cybernetic controller can be implemented by a resolved momentum control with the block diagram shown in Fig. 8 [11].

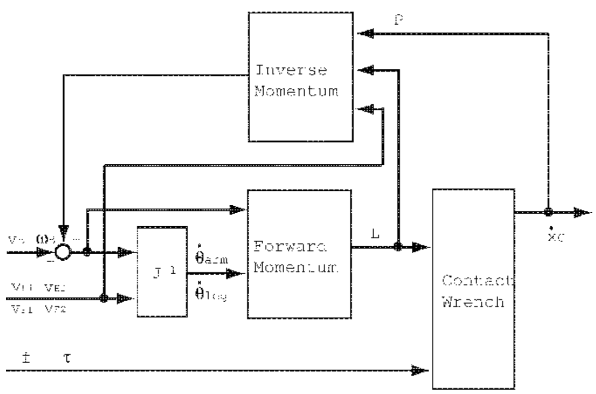

Fig. 8 Block diagram of the resolved momentum control

The controller assumes that the suit has sensors to find and $v_{H1}, v_{H2}, v_{F1}, v_{F2}, v_B$, and $\omega_{H1}, \omega_{H2}, \omega_{F1,}\omega_{F2}, \omega_B$, force and torque sensors to measure f, τ. The angular velocity of the arms and legs giving L can then be found by inverse kinematics, and a modified X_G can be computed from a desired trajectory of f, τ to ensure the contact stability of the feet with the floor by solving the contact wrench equations. Next, modified v_{B1}, ω_B are found from the modified P by solving the inverse momentum equations, and modified angular velocities are computed by inverse kinematics. The suit can then trigger the corresponding muscles to generate the desired angular velocities.

This cybernetic controller based on contact wrench control requires precise sensors to find angular velocities and contact forces and torques, and actuators for all joints. This cannot be achieved using the current prototype, so experimental evaluation of such a controller is beyond the scope of this paper.

IV. Experimental Evaluation Method

We experimentally examined the cybernetic controller based on virtual passive walk using a prototype motion control suit. The passive walk uses the compass-like model shown in Fig. 6, which has an ankle joint and a hip joint with no knee joint. The suit has IMU-based sensors to measure lower leg orientations. Though the leg length should vary with knee angle, we assume that each leg length is fixed.

Solving Eq. (3) gives desired torques of the ankle and hip joints, but Eq. (3) is an indefinite equation. To solve it, let $u_1 = \mu\, u_2$ for simplicity [7, 8]. Then the solution is given by

$$Su = \begin{bmatrix} \mu+1 \\ -1 \end{bmatrix} \frac{Mg\tan\phi \dot{X}_g - \zeta(E - Mg\tan\phi X_g)}{(\mu+1)\dot{\theta}_1 - \dot{\theta}_2} \tag{5}$$

The control assist suit does not generate the torques in Eq. (5). Instead, it triggers motions of the corresponding joints by angular velocities proportional to the torques in Eq. (5).

The experimental setup is as follows. The subject, a healthy adult, wears the suit and starts to walk with an upright posture. Figure 9 shows the subject wearing the suit.

The orientation sensors try to find θ_1 and θ_2, and Eq. (5) gives the desired torque for the virtual passive walk. The trigger angular velocity is

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \alpha\, Su\,,$$

where α is a constant to determine the magnitude of the triggers. When a swinging leg contacts the floor, it becomes the supporting leg and vice versa, so θ_1 and θ_2 must be exchanged to find the feedback control given by Eq. (5). This contact is detected by a pressure sensor (SEN-08685; SparkFun Electronics), shown in Fig. 10. Figure 11 shows an example of sensor data from around the contact point. The flags in the graphs after Fig.11 mean the following. If flag number is 0, then right foot, 1 is left foot, 2 is both feet land on the ground.

Fig. 9 Subject wearing the suit

Fig. 10 Pressure sensor to detect contact

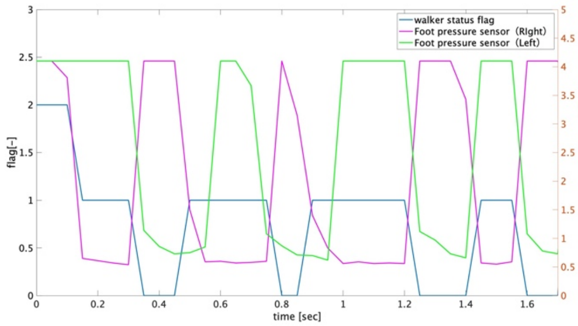

Fig. 11 Example pressure sensor data.

Figure 12 shows an example of experiments in which the Kalman filter is applied to the left and right IMU sensors to estimate the leg angle.

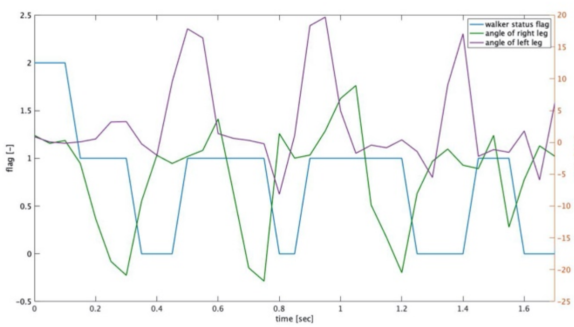

Fig. 12 Example of lower leg orientation

Fig13 shows an example of generation of control target value.

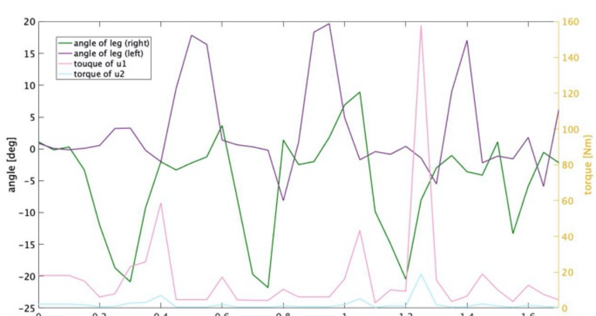

Fig. 13 Generation of control target value

We drove the linear actuators to investigate whether the subject could feel the triggers, and confirmed that the subject could feel them to invoke muscle flexion.

Further experimental evaluations are required to prove that the cybernetic controller can improve motion stability.

Conclusions

We proposed the concept of a control assist suit to assist human motion control instead of providing power assistance. The suit includes motion sensors, a cybernetic controller, and actuators that trigger human motions according to commands from the controller. The controller was implemented based on a virtual passive walking model, and we confirmed that feasibility was expected of a motion control assist suit..

Future research will examine user muscle response triggered by control assist, and will investigate the required specifications for linear actuator strength, speed, and travel distance. We must also examine configurations of actuator and sensor locations.

There are various possibilities for the cybernetic controller. In addition, many control algorithms have been proposed for humanoid robots [12, 13, 14, 15], and it would be worthwhile to search for optimal algorithms to be deployed as cybernetic controllers.

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