Dynamic assessment of supernumerary tails for balance augmentation

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Abstract— **Humans maintain balance in upright stance thanks to neuro-muscular sensory properties; however, still exhibit postural sway characteristics. This work assesses the ability of three one-degree-of-freedom supernumerary robotic tails for balance augmentation to accelerate the centre-of-mass of a human wearer using manipulability ellipsoids and metrics.**

I. INTRODUCTION

Humans are inherently unstable when standing, maintaining upright balance due to neuromuscular sensory properties. Thus, it is valid to model a human in an upright pose as an inherently unstable inverted pendulum[1]. Nevertheless, postural sway is exhibited in quiet stance; with factors such as muscle fatigue, neurological disorders, and loss of vestibular function contributing and exacerbating such phenomena. If this sway causes the centre of mass (CoM) to exceed the base of support (BoS), balance can be lost.

Research has been conducted to augment human balance with robotic assistance. Gyroscopic systems and supernumerary robotic tails (SRTs) mounted posterior to the trunk have been used. In gyroscopic systems, the principal of precession is utilised to counteract the torque caused by postural sway [2] while SRTs take inspiration from animals, utilising swinging inertia for balance augmentation [3]. Whilst these systems provide balance, they come at the cost of significant added mass of 10-16 kg with an extra 10 kg shown to be detrimental to the motion of human natural limbs [4].

Our recent work showed via simulation that a 5 kg one-degree-of-freedom (dof) swinging arc tail was sufficient to balance an 82 kg human carrying a 5 kg load with severely impaired neuromuscular control [5]. A state feedback controller was systematically designed which harnessed insight into design considerations of SRTs and potential impact on muscle loading. However, an assessment methodology of SRTs to dynamically augment balance of a human is required. In this work, we utilise the concept of manipulability to assess the dynamic properties of three one-dof SRTs. Section II provides an overview of required theory and section III provides preliminary results.

II. DYNAMIC MANIPULABILITY ASSESSMENT

Dynamic manipulability measures have been proposed to indicate the feasible operational space accelerations that the generalised actuator forces in joint space can create. Azad et al. [6] proposed the bounded-torque weighting matrix which assess the role of actuators in the dynamic manipulability of a particular point of a robot manipulator. This assessment is applicable to SRTs.

The inverse dynamic model (IDM) of a mechanism is

$$\mathbf{u} = \mathbf{M}_q\left(\mathbf{q}\right)\ddot{\mathbf{q}} + \mathbf{C}_q\left(\mathbf{q},\dot{\mathbf{q}}\right) + \mathbf{G}_q\left(\mathbf{q}\right) \tag{1}$$

where $\mathbf{q}$ are the generalised joint coordinates, $\mathbf{M}_q$ is the $n \times n$ generalised inertia matrix, $\mathbf{C}_q$ is an $n \times 1$ vector related to the centripetal and Coriolis torques, $\mathbf{G}_q$ the vector of generalised gravity forces and $\mathbf{u}$ are generalised actuator forces.

Rearranging Eq. (1), the forward dynamic model (FDM) can be written as

$$\ddot{\mathbf{q}} = -\mathbf{M}_q^{-1}\left(\mathbf{C}_q\left(\mathbf{q},\dot{\mathbf{q}}\right) + \mathbf{G}_q\left(\mathbf{q}\right)\right) + \mathbf{M}_q^{-1}\mathbf{u} \tag{2}$$

Through use of the Jacobian relationship $\mathbf{t} = \mathbf{J}\dot{\mathbf{q}}$, Eq. (2) can be written in operational space as

$$\dot{\mathbf{t}} = -\mathbf{J}\mathbf{M}_q^{-1}\left(\mathbf{C}_q + \mathbf{G}_q\right) + \mathbf{J}\mathbf{M}_q^{-1}\mathbf{u} = \dot{\mathbf{t}}_{cg} + \mathbf{J}_t\mathbf{u} \tag{3}$$

where $\mathbf{t}$ represents the twist of the CoM and $\dot{\mathbf{t}}_{cg}$ the operational acceleration due to gravitational and centripetal/Coriolis effects.

Hence, the generalised forces in terms of the operational acceleration of the CoM are

$$\mathbf{u} = \mathbf{J}_t^{\dagger}\left(\dot{\mathbf{t}} - \dot{\mathbf{t}}_{cg}\right) + \mathbf{N}\mathbf{u}_0 \tag{4}$$

where $\mathbf{J}_t^{\dagger} = \mathbf{W}^{-1}\mathbf{J}_t^T\left(\mathbf{J}_t\mathbf{W}^{-1}\mathbf{J}_t\right)$ is a pseudo-inverse, $\mathbf{W}$ a $k \times k$ weight matrix and $\mathbf{N}$ is a null space projector of $\mathbf{J}_t$.

To investigate the ability of the actuators to accelerate the CoM, a unit weighted norm is used, i.e.

$$\mathbf{u}^T\mathbf{W}\mathbf{u} \leq 1 \tag{5}$$

Substitution of Eq. (4) into Eq. 5 yields [6]

$$0 \leq \left(\dot{\mathbf{t}} - \dot{\mathbf{t}}_{vg}\right)^T\left(\mathbf{J}_t\mathbf{W}^{-1}\mathbf{J}_t^T\right)^{-1}\left(\dot{\mathbf{t}} - \dot{\mathbf{t}}_{vg}\right) \leq 1 \tag{6}$$

which represents a dynamic manipulability ellipsoid in the operational acceleration space of the CoM.

One option for a meaningful weighting matrix is [6]

$$\mathbf{W} = \frac{1}{k}\mathtt{diag}\left(\left[\frac{1}{u_{1max}^2} \cdots \frac{1}{u_{kmax}^2}\right]\right) \tag{7}$$

which represents a bound on the maximum available torque for each of the k actuators.

Typically, it is desired to accelerate a robot between two points in a particular direction $\mathbf{v}$. Letting $\mathbf{A} = \mathbf{J}_t\mathbf{W}^{-1}\mathbf{J}_t^T$, the following distance metric can be defined as [6]

$$\delta = \frac{\|\mathbf{v}\|}{\sqrt{\mathbf{v}^T\mathbf{A}^{-1}\mathbf{v}}} \tag{8}$$

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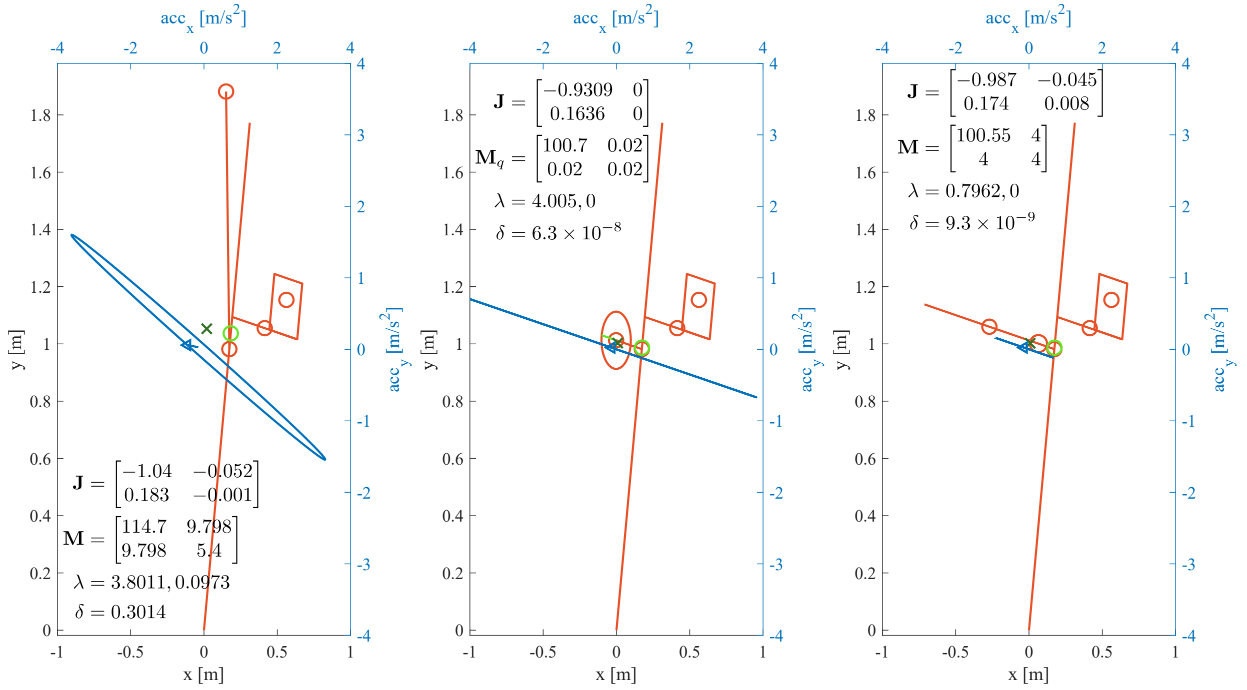

(a) Swinging Arc SRT (b) Reaction Wheel SRT (c) Linear Counter Mass SRT

Fig. 1: The configuration of the three SRTs about to exceed the BoS. The manipulability ellipses have principal axes λ. The dark green cross indicates the location of the CoM in upright stance

which is the maximum acceleration in the desired direction physically achievable with the actuator combination.

III. PRELIMINARY RESULTS

Three one-dof tails are proposed, all mounted to a human at the location of the CoM in an upright stance. The three tails are a linear counter mass (LCM) that slides along a rail, a reaction wheel (RW) mounted a fix distance posterior to the trunk, and a revolute swinging arc tail. In the case of the LCM and arc tails, the length of the rail/tail was chosen as 0.9 m whilst for the RW the radius was chosen as 0.1 m with tail satisfying static balance in upright pose. All tails had mass of 5 kg. A human of height 1.8 m with CoM at 0.997 m, mass 82 kg and inertia about the sagittal plane of 12.92 kg-m^2 was simulated. It was assumed that the human had full neuro-muscular control, represented by maximal torque of 30 N-m [7]. For conceptual ease, the actuators of the tail were assumed to have maximums an order of magnitude higher than this, i.e. for the RW and Arc 300 N-m and 300 N for the LCM. The human was simulated as one-dof inverted pendulum at an angle of 8°, i.e. just before the BoS is exceeded. The tails were assumed to be in the configuration that maintains static balance in upright stance. Figure 1 illustrates the configuration of the three human-SRT systems and the associated manipulability ellipses given by Eq. (6). The distance δ is in the direction correlating to upright stance. It is evident that the ability of the LCM and RW SRTs to accelerate the CoM in multiple directions is diminshed as the ellipses are straight lines. However, the arc SRT has greater ability as indicated by the ellipses. Clearly from $\mathbf{M}_q$ and $\mathbf{J}$ the kinematic structure and thus generalised inertia matrix is critical in accelerating the CoM, i.e. larger coupling inertia terms and non singular Jacobian.

IV. FUTURE WORK

This work highlights the ability of SRTs to accelerate the CoM. As coupling inertia is significant in increasing CoM acceleration, multi-dof SRTs will be explored. The intended application is in industrial load carrying tasks where workers are maintaining upright stance for prolonged periods. As such, muscle activation effects of SRTs will be considered.

REFERENCES

[1] R. J. Peterka, “Postural control model interpretation of stabilogram diffusion analysis,” *Biological Cybernetics*, vol. 82, pp. 335–343, 2000.

[2] D. Lemus, A. Berry, S. Jabeen, C. Jayaraman, K. Hohl, F. C. T. van der Helm, A. Jayaraman, and H. Vallery, “Controller synthesis and clinical exploration of wearable gyroscopic actuators to support human balance,” *Scientific Reports*, vol. 10, p. 10412, 12 2020.

[3] A. Maekawa, K. Kawamura, and M. Inami, “Dynamic assistance for human balancing with inertia of a wearable robotic appendage,” in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2020, pp. 4077–4082.

[4] J. H. Meuleman, E. H. van Asseldonk, and H. van der Kooij, “The effect of directional inertias added to pelvis and ankle on gait,” *Journal of NeuroEngineering and Rehabilitation*, vol. 10, p. 40, 2013.

[5] S. Abeywardena, E. Anwar, S. Miller, and I. Farkhatdinov, “Human balance augmentation via a supernumerary robotic tail,” in *44th IEEE Engineering in Medicine and Biology Conference*, 2022.

[6] M. Azad, J. Baic, and M. Mistry, “Effects of the weighting matrix on dynamic manipulability of robots,” *Autonomous Robots*, vol. 43, pp. 1867–1879, 2019.

[7] A. Moraux, A. Canal, G. Ollivier, I. Ledoux, V. Doppler, C. Payan, and J.-Y. Hogrel, “Ankle dorsi- and plantar-flexion torques measured by dynamometry in healthy subjects from 5 to 80years,” *BMC Musculoskeletal Disorders*, vol. 14, no. 1, p. 104, 2013.