Design and Evaluation of a Series-Elastic Gyroscopic Actuator for Balance Assistance

Conference Paper · July 2021

DOI: 10.1109/AIM46487.2021.9517659

Authors' version
presented at the IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) 12-16 July, 2021. DOI: 10.1109/AIM46487.2021.9517659

Design and Evaluation of a Series-Elastic Gyroscopic Actuator for Balance Assistance

1st Charlotte Marquardt
Institute of Anthropomatics and Robotics,
Karlsruhe Institute of Technology
Karlsruhe, DE
charlotte.marquardt@kit.edu

2nd Daniel Lemus
Department of Rehabilitation Medicine,
Erasmus MC, Rotterdam, NL
& Delft University of Technology, Delft, NL
d.lemusperez@erasmusmc.nl

3rd Cory Meijneke
Electrical and Mechanical Support Division
Delft University of Technology
Delft, NL
c.meijneke@tudelft.nl

Compared to our first prototype [8], this second prototype has an additional Degree of Freedom (DoF), an inner gimbal. This passive DoF incorporates a compliant element, and it also allows completely decoupling the flywheel’s orientation from the user, to ensure safety by halting any transmission of

The general proposed control architecture (Fig. 4) comprises three different control levels. The controller of the highest level (green) detects the loss of balance of the wearer and keeps the wearer balanced. This high-level controller provides the reference torque $M_{\mathrm{CMG;ref}}$ online (in analogy to [10]), which is tracked by a torque controller in the middle layer (blue), resulting in the reference gimbal velocity $\_{\mathrm{ref}}$. Within the low-level control (orange), a PI controller ensures tracking of the commanded gimbal velocity $\_{\mathrm{ref}}$. A similar PI controller ensures constant flywheel velocity .

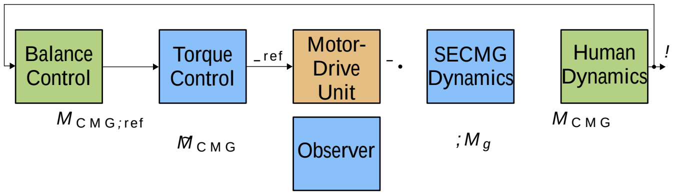

Fig. 4. Proposed observer-based control approach. The dashed box highlights the scope of this paper.

An observer provides the approximated gyroscopic output torque $\tilde{M}_{\mathrm{CMG}}$, based on the gimbal velocity, the deflection angle of the compliant gimbal, and human motion.

For the torque controller in the middle layer, the SECMG could in principle be modeled as a Double-Gimbal Control Moment Gyroscope (DGCMG), because of its second, inner gimbal frame. However, its principle of operation resembles more that of a SGCMG, because the inner gimbal frame is constrained by the compliant element. As we allow only small deflections of the inner gimbal, we approximate its dynamics as a SGCMG.

III. EVALUATION

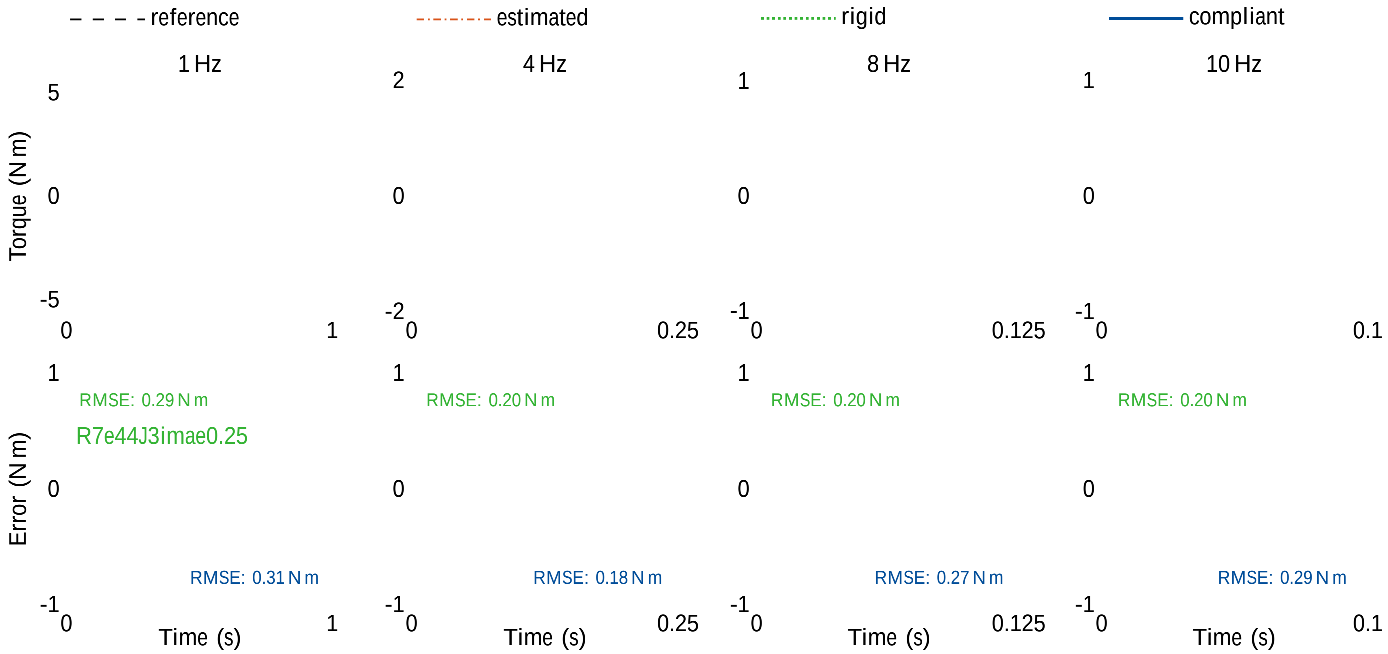

Fig. 6. Reference, estimated and both measured load cell torques of the compliant (estimate44J3f)-330(the)-331(compliant)-331((estimate44J3f)-330(the)-

The dynamic retardation is displayed in Fig. 10 as the difference in phase of the frequency response of the angular deflection and the gyroscopic output torque. The SPIDEX® shows a slightly decreasing retardation angle, beginning at about −10° up to 0.4 Hz, which decreases more strongly with an increased noise for higher frequencies.

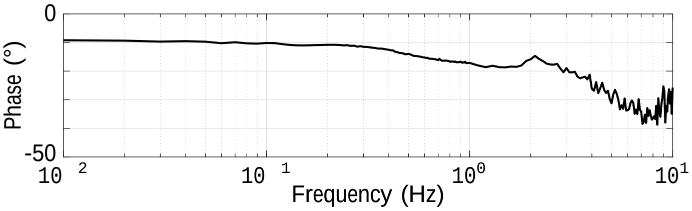

Fig. 10. Dynamic retardation of the viscoelastic material represented as the difference in phase of the frequency response of the angular deflection and the gyroscopic output torque.

V. DISCUSSION

A. Torque Tracking Performance and Sensing Limitations

Comparing the frequency response of the compliant and the rigid CMG, the inclusion of a viscoelastic element does not appear to reduce performance. Taking into account the standard physiological time delay of about 150 ms to 200 ms in human postural control [24], [25], both configurations exceed the bandwidth requirements for application in human balance assistance. So, integration of series-(visco)elasticity in a CMG seems to be applicable without a relevant limitation of bandwidth.

However, the stationary experimental setup limits conclusions regarding the wearable application, particularly regarding the influence of human motion or other unpredictable perturbations of the environment. The human upper body's angular velocity vector has to be considered when controlling the device, as it is expected to affect the torque tracking performance as well as the accuracy of the torque estimation. Under those circumstances, the dedicated viscoelastic torque sensing is expected to show a key advantage compared to the model-based torque estimation using gimbal velocity.

Further effects due to the slight deflection of the inner gimbal while modeling the system as a SGCMG instead of a DGCMG can be neglected. Any losses in the gyroscopic exceeds bandwidth requirements of its application in human augmentation at about 5 Hz.

Characterization of the viscoelastic material to enable it as an active torque sensor revealed a non-linear torque-deflection relation and a hysteresis, which is likely due to backlash in the mechanical components. Even though the high stiffness of the chosen material prevents relevant losses to the gyroscopic output torque, it exacerbates the effect of backlash on the deflection-based torque sensing. Therefore, future work is needed to reduce this effect.

p. 139–8406-350(V)30(ol.)1
vol. 310 Jaun.-310(0)]TJ0 g 0 G -175.061-8.966 Td [([1])]TJ0 g 0 G [-625(H.)-3632.Aandin alastic”PIEEE/RSJ-2546mItervntionale oenht-2546meobois-3567indPumar

Overall, the concept of a SECMG appears feasible, but it has to be determined if the benefits outweigh its limitations not only regarding the inclusion of a viscoelastic material, but also the added mass and envelope due to the required additional gimbal.

ACKNOWLEDGMENT

This research was supported by the U.S. Department of Education, National Institute on Disability and Rehabilitation Research, NIDRR-RERC, Grant No. H133E120010 and the Innovational Research Incentives Scheme Vidi with Project No. 14865, from The Netherlands Organization for Scientific Research (NWO). Charlotte Marquardt was supported by an ERASMUS+ traineeship grant and by the INOPRO project (16SV7665) funded by the German Federal Ministry of Education and Research (BMBF) .

The authors would like to thank Saher Jabeen, Andrew Berry, Andries Oort, Giel Hermans, Jan van Frankenhuyzen, and Hyperion Technologies B.V. for their contributions to this work over the years and Tamim Asfour for the overall support.

SUPPLEMENTARY MATERIALS

In order to allow verification and review of our data and code, we have uploaded the resources to an open-access public repository available in the 4TU.ResearchData [23].

REFERENCES

[1] H. Stolze, S. Klebe, C. Zechlin, C. Baecker, L. Friege, and G. Deuschl, “Falls in frequent neurological diseases,” *Journal of Neurology*, vol. 251, pp. 79–84, Jan 2004.

[2] D. Winter, “Human balance and posture control during standing and walking,” *Gait & Posture*, vol. 3, no. 4, pp. 193 – 214, 1995.

[3] K. Delbaere, C. Sherrington, and S. R. Lord, “Falls prevention interventions,” in *Osteoporosis (Fourth Edition)*, R. Marcus, D. Feldman, D. W. Dempster, M. Luckey, and J. A. Cauley, Eds. San Diego: Academic Press, 2013, pp. 1649 – 1666.

[4] F. A. Leve, B. J. Hamilton, and M. A. Peck, *Spacecraft Momentum Control Systems*, ser. Space Technology Library. Springer, 2015, vol. 34.

[5]