On Robotic in-Orbit Assembly of Large Aperture Space Telescopes

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***Abstract*— Space has found itself amidst numerous missions benefitting the life on Earth and for mankind to explore further. The space community has been in the move of launching various on-orbit missions, tackling the extremities of the space environment, with the use of robots, for performing tasks like assembly, maintenance, repairs, etc. The urge to explore further in the universe for scientific benefits has found the rise of modular Large-Space Telescopes (LASTs). With respect to the challenges of the in-space assembly of LAST, a five Degrees-of-Freedom (DoF) End-Over-End Walking Robot (E-Walker) is presented in this paper. The Dynamical Model and Gait Pattern of the E-Walker is discussed with reference to the different phases of its motion. For the initial verification of the E-Walker model, a PID controller was used to make the E-Walker follow the desired trajectory. A mission concept discussing a potential strategy of assembling a 25m LAST with 342 Primary Mirror Units (PMUs) is briefly discussed. Simulation results show the precise tracking of the E-Walker along a desired trajectory is achieved without exceeding the joint torques.**

Keywords—End-Over-End Walking Robot, Gait Pattern, Large Aperture Space Telescope, On-Orbit Assembly, Mission Concept

I. INTRODUCTION

The invention of the telescope in 1608 saw the origin of a new spectrum of research for astronomers. The aspiration towards time-travelling and the rate of expansion of the universe resulted in the development of numerous Earth-based Space Observatories. However, the light captured by the telescope on the ground has to overcome the vast and protective shield of the Earth, the atmosphere. Cloud cover, light pollution and turbulence result in atmospheric distortion, blurring the captured light. To overcome these problems, initially, astronomers attached the telescopes to giant balloons to operate the telescope above the Earth's lower atmosphere, which saw the beginning of the trend towards Space Telescopes.

Ever since the launch of the Hubble Space Telescope (HST) with a Primary Mirror (PM) of 2.4m in the 1990s, it has provided a significant amount of data of around 500 million years after the Big Bang. Its successor, the James Webb Space Telescope (JWST), with a PM of 6.5m to be launched by late 2021 would have capabilities to see 100 million years post the bang. However, the dimensioning of these telescopes still limits the goal of imaging distant objects, requiring telescopes with a much larger aperture. Large Aperture Space Telescopes (LAST) would provide solutions to the current requirements of higher spatial resolution and signal to noise ratio [1, 2]. Nevertheless, LASTs cannot be manufactured monolithically; even if it has a monolithic structure, it cannot be stowed into the contemporary launch vehicles, to be self-deployable as in the case of JWST, requiring a segmented design [3]. These drawbacks of the current state-of-the-art provide the vision for in-orbit robotic assembly of these modular mirror segments. With Robotics, Automation and Autonomous Systems (RAAS) swiftly growing for Space and terrestrial applications in extreme environmental conditions, this paper presents a robotic architecture in the form of an End-Over-End Walking Robot (E-Walker) to meet the goal of in-orbit assembly of a 25m LAST [4]. A Mission Concept to carry out the assembly is discussed briefly along with the simulation results showcasing the E-Walker's Motion along the desired trajectory.

II. E-WALKER: DYNAMIC MODEL AND CONTROL

Inspired by the architecture of the Canadarm2 on top of the International Space Station (ISS) and the soon to be launched European Robotic Arm (ERA), a 5 DoF E-Walker is presented in this paper. With a cyclic gait pattern, each cycle of the E-Walker's motion is comprised of two phases. Individually, in each phase, the E-Walker has the features of a fixed-to-base robotic manipulator. With Joints 1-5 marked as J_1-J_5, Fig. 1 shows a complete cycle of the E-Walker's motion from an initial position. Fig. 1b shows Phase-1, where Joint 1 is fixed to the base and Joint 5's motion is tracked. In Phase-2, shown in Fig. 1c, J_5 is fixed and J_1's motion is tracked. To facilitate the motion in a real-mission scenario, the base spacecraft and the truss have connector points incorporated in their design.

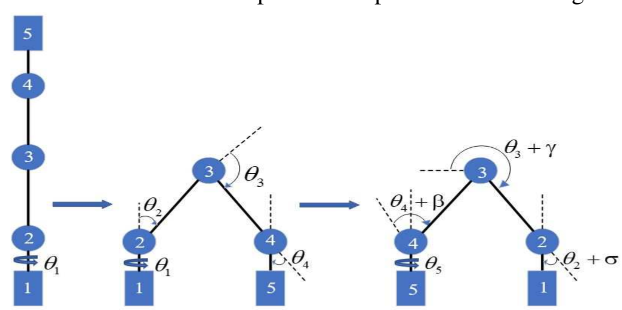

Fig. 1. Cycle-1 Walking Pattern of an E-Walker: (a) Initial Position (b) Phase-1 and (c) Phase-2

The dynamic equation of the torque is given by: $\mathbf{D}(\theta)\ddot{\boldsymbol{\theta}}+\mathbf{C}(\theta,\dot{\theta})\dot{\boldsymbol{\theta}}+\mathbf{G}(\theta)=\boldsymbol{\tau}$, where $\mathbf{D}(\theta)\in\mathbb{R}^{5\times5}$ is the mass matrix and is useful to calculate $\mathbf{C}(\theta,\dot{\theta})\in\mathbb{R}^{5\times5}$ which comprises of the Coriolis and centrifugal terms. $\mathbf{G}(\theta)\in\mathbb{R}^{5\times1}$ is the Gravity matrix. For the initial verification of the E-Walker model, a PID controller is used, governed by the control law $\boldsymbol{\tau}=\mathbf{D}(\theta)\boldsymbol{\tau}'+\mathbf{C}(\theta,\dot{\theta})\dot{\boldsymbol{\theta}}+\mathbf{G}(\theta)$, where, $\boldsymbol{\tau}'=\ddot{\boldsymbol{\theta}}^{\boldsymbol{d}}+\boldsymbol{K_p}(\boldsymbol{\theta}^{\boldsymbol{d}}-\boldsymbol{\theta})+\boldsymbol{K_i}\int(\boldsymbol{\theta}^{\boldsymbol{d}}-\boldsymbol{\theta})\mathrm{dt}+\boldsymbol{K_d}(\dot{\boldsymbol{\theta}}^{\boldsymbol{d}}-\dot{\boldsymbol{\theta}})$.

III. MISSION CONCEPT

The presented mission concept has two E-Walkers, namely, EW_1 and EW_2 working in collaboration to assemble the 25m LAST. The 25m Primary Mirror (PM) of LAST to be robotically assembled is made of 18 Primary Mirror Segments (PMSs). Each PMS is made of 19 hexagonal Primary Mirror Units (PMUs). The PMUs would be stacked in a storage spacecraft to be lifted off to dock with the base spacecraft (B_{sc}) to serve as a collection point during the assembly. The PMUs can be made available in form of individual mirror modules or fractional PMS [3]. Both the E-Walkers would have the ability to walk over the B_{sc} and truss. For a safe assembly of the PM, the PMUs are to be placed on a backplane with connector points. The E-Walker would be facilitated with visual guidance to grasp the PMUs by the connector points, without directly interacting with the mirror.

In the proposed LAST mission concept, EW_1 is responsible for the assembly on the left half of the truss whereas EW_2 will deal with the right-half assembly. The mission concept of operations (ConOps) is divided into two modes. In Mode 1, both the E-Walkers work together to assemble the majority of the right and left-half outer rings. Initially, EW_1 and EW_2, from their respective connector points on the B_{sc}, assembles a PMS using the available PMUs in the desired inner ring position. The 19 PMUs, which makes 1 PMS, is shared almost equally between the E-Walkers depending on the half-in-focus for assembly. If the right-half is to be assembled, then EW_1 places few extra PMUs compared to EW_2 to assemble the PMS. Thereafter, EW_2 walks onto the respective truss connector points to place the assembled PMS, while EW_1 begins assembling the second PMS. Post placing the PMS, EW_2 climbs back onto the B_{sc} to assist EW_1 in the PMS assembly. Once the majority of the right-half outer ring is assembled, EW_1 takes the role of walking around the truss to place the assembled PMS, whilst assisting EW_2 in assembling the PMUs. Here, EW_2 places few extra PMUs to assemble each PMS. Once the majority of the left-half outer ring is assembled, the first phase of assembly is complete. The operation now shifts to Mode 2, where EW_1 and EW_2 are seen working independently in their halves, assembling and placing the PMSs for the left-over mirror positions. A detailed workflow for a practical LAST assembly, including the shared responsibilities amongst the E-Walkers to assemble each PMS using the PMUs is under development and results will be published separately.

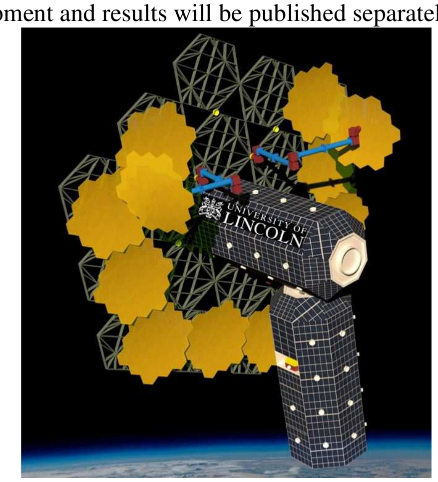

Fig. 1. Mission Concept: Two E-Walkers working in Collaboration

IV. SIMULATION RESULTS AND DISCUSSION

For the simulations, the following parameters were taken into consideration: Joint configuration A = [0;0;0;0;0], B = [0;30;120;30;0], C = [0; -30; -120; -30; 0], Link lengths = 0.3m, Offset = 0.1m. Phase-1 (A-B) is run from t = 0:10s, while Phase-2 (C-B) is run from t = 10:30s. Post completion of Phase-1, the joint configuration attained by the E-Walker (here, B) is made equal to the required starting configuration for Phase-2 (C). The simulation results shown in Fig.4, shows the joint angles being successfully tracked. From Fig. 4(c), it is seen that in Phase-1, J_2 produces the maximum negative torque, as the E-Walker is moving in the direction of gravity. In Phase-2, J_4 experiences a maximum positive torque in the first half of the motion, whereas in the other-half it produces a negative torque similar to Phase-1. During Phase-1, the E-walker traverses 0.3m. In Phase-2, the E-walker completes a full-motion, traversing 0.6 metres along the Y-axis. These results matched the design requirements.

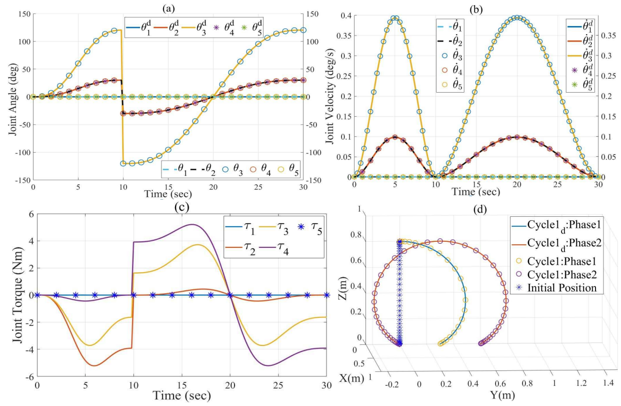

Fig. 4: Outputs: (a) Joint Angles, (b) Joint Velocities, (c) Joint Torques under gravity (d) Trajectory

V. CONCLUSION AND FUTURE ENHANCEMENTS

In this paper, a dynamic model of an E-Walker was presented to assemble a 25m LAST. For the initial verification of the E-Walker model, a PID controller was used to make the E-Walker follow the desired trajectory. A mission concept discussing a potential strategy of assembling the 342PMUs is briefly discussed. Future research involves the analysis of the E-Walker model with other linear and non-linear controllers, realising a real-mission trajectory based on the different mission scenarios and coupling the E-Walker Dynamics with the base spacecraft dynamics. The E-Walker has to be also tested in Earth analogue conditions to assess the assembly of the secondary mirror, truss and also a precursor mission using a 2.5m/5m telescope.

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