Collaborative Rigid Body Manipulation Toward Heterogeneous Humanoids

Hashim Hameed[1] and Dr. Paul Oh[2]

***Abstract*—This paper demonstrates the utilization of two humanoid robots possessing heterogeneous physical and computational characteristics for the purpose of manipulating a rigid body. The non-symmetric characteristics are considered and compensated for as related to traversal and task execution. Permission of minimal error in manipulation further emphasizes discrepancy in compensation parameters and the requirement of cooperative coordination in work towards generalization. Experiments are conducted using modified DARwIn-OP humanoid robots which perform detection and alignment, approach, collaborative grasping, and collaborative traversal relative to a rigid body. Actions are informed by computer vision, predetermined "limb" actuation, or predetermined traversal dependent on the task's stage. This push toward stability within both independent and collaborative task execution operates as a base for research and deployment of heterogeneous actors, permitting generalized operation and execution beyond capabilities of a single actor.**

I. Introduction

Humanoid robotics is often characterized by generalization, with consistent emulation of the human form across research and industry often resultant from the goal of enabling an actor to complete numerous tasks ranging in requirements of dexterity, perception, or environmental traversal. These requirements are met by novel and iterative approaches to obstructions such as actor limb coordination, object manipulation considerate of posture, and overall bipedal walking control [1] [2] [3]. This forefront objective of generalization for the purpose of task completion is affected greatly by multi-actor collaboration, with limitations considerate of a single actor being compensated for via coordinated effort. This work's motivation is seen by the extent to which compensation for differences in morphology, sensor fidelity, and/or locomotion biases between actors may further this effort. This is accomplished through maintenance in stability, temporal and physical coordination, as well as a generalizable execution framework.

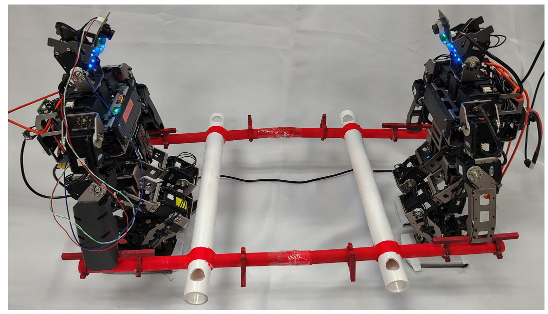

Fig. 1: Actor A (Right) & Actor B (Left) Carrying Stretcher

Progress is made considerate of quadrupedic locomotion research as bridged with humanoid robotics and application of such to the execution of stages of larger collaborative tasks. This is so through the use of physically and computationally dissimilar actors which demonstrate differences in gait reflective of discrepancies seen in alternative realized systems (Fig. 1), providing the foundation for further generalization in future works.

Within the presented task of manipulation of a rigid body, in this case a custom scaled-down stretcher, sections of movement which can be discriminated on the basis of function or means of implementation are considered as "stages", implemented as a means of managing complexity. The mentioned stages include visual detection and alignment, approach, collaborative grasping, and collaborative traversal, and are assessed individually rather than in the context of an overall movement or task. Stability at each stage is evaluated in a distinct manner dependent on the stage being executed. Particularly, search and alignment is assessed via time taken to recognize visual stimulus and align with it following partial obfuscation, grasping and approach via stability throughout movement as measured by actor internal IMU data, and movement via rigid body external IMU data.

The focus of this paper is to consider and iterate

[1] Department of Electrical and Computer Engineering, University of Nevada, Las Vegas. Las Vegas, NV, USA hameeh1@unlv.nevada.edu

[2] IEEE Fellow, Department of Mechanical Engineering, University of Nevada, Las Vegas. Las Vegas, NV, USA paul.oh@unlv.edu

upon the execution of cooperative tasks by heterogeneous actors to compensate for disparate conditions or form factor(s) which may affect gait and coordination. Inevitable progress within the humanoid field additionally stresses the importance of such, with pronounced differences between manufactures and product generations in time, inevitably appearing and causing cross-generational compatibility obstacles [4] [5]. Compensation for incongruence serves to assist in achieving aid or substitution of human actors in instances of labor requiring the use of multiple actors, and cooperative automation through the humanoid form factor allows for a generalization over specialization approach.

II. Related Work

Consideration of prior works primarily consists of cooperative manipulation using systems of automated actors, with the few applications of such in the context of non-symmetric humanoid actors being a great motivator for this paper. The utilization of non-humanoid actors for such a purpose is documented to a greater extent considering the execution of specialized or simplified tasks to highlight particular matters of research interest often benefit from or even require non-humanoid candidates. Often these candidates consist of wheeled mobile or otherwise constrained actors depending on the task or research considered [6].

Research regarding heterogeneous actors, though not often considering humanoid systems, provide additional insight. An example lies in Yi et al. [7], presenting a multi-agent pickup and delivery framework permitting collaboration of contrasting mobile actors, utilizing dynamic pairing and an auction-based planner for partial trajectory planning to produce more efficient coordination. Even seeing task completion as an aside, examples such as Xing et al. [8] provide a greater depth of consideration for matters such as size variance in the context of collision avoidance, providing a dynamic means of such to overcome the barriers of static zone control methods. An additional example bridging to the humanoid world additionally comes from Andre M. Santana and Adelardo A.D. Medeiros [9] whom consider locomotion path planning through means of the pose estimation between a wheeled and humanoid actor, with the former utilizing the latter to translate in a manner considerate of viewing angle restrictions. These research instances parallel and showcase the difficulties of varying locomotion characteristics of systems, perception restrictions, and morphology affect cooperative task execution stability.

A focus on non-humanoid actors within the context of multi-actor systems maintains prevalence, with instances of a shift in this focus more often considering homogeneous teams reliant on symmetric assumptions. An example is seen in work by Wen et al. [10] wherein two NAO humanoid platforms transport a stretcher rigid body using distributed model predictive control, with ZMP-based trajectories coordinated between a leader and follower via networked communication. In this case, the identical hardware sees a mirroring in gait and a common controller, overall simplifying coordination between the actors. Similarly, Zhong et al. [11] study two homogeneous humanoid candidates for the purpose of cooperatively carrying a weighted object. This would deal with optimizing parameterization to minimize energy consumption whilst maintaining ZMP stability for the pair's cooperative gait, to which the actors step in accordance to the generated gait pattern. These works clearly progress the goal of generalization discussed through cooperation of multiple actors, though show how a lack of consideration for potential discrepancies between actors remains a far less explored territory.

Of studies regarding cooperative humanoids, Stephen M. and Daniel L. [12] explore an additional case of a stretcher, with a great deal of emphasis on the analogous quadrupedic locomotion and gait that stems from the manipulation of a rigid body and synchronization of actor movement. The mentioned work would additionally develop a means of task completion built upon within this paper, with each stage of an overall task being decomposed and assessed prior to actor engagement so as to bolster efficiency and isolate relevant execution parameters. Such serves as a solid basis of study, with the potential benefits of synchronized multi-humanoid movement stability being explored.

To further the goal of actor generalization, this paper seeks to build off of the work of both heterogeneous non-humanoids and homogeneous humanoids. The unique dynamics of the actors and the shared task decomposition methodology are considered to compensate for the differences between the platforms. Such is accomplished through closed-loop perception continuously informing coordination strategy, prioritizing autonomy and adaptability. The relative absence of such consideration and strategy within prior underscores the novelty of the cross-platform collaboration considered in this work.

III. Methodology

The stretcher rigid body considered throughout this paper is of dimensions of $24\text{x}15\frac{1}{2}$ inches, with 11 inches

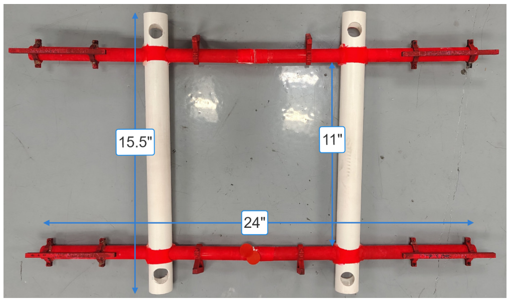

Fig. 2: Stretcher Dimensions

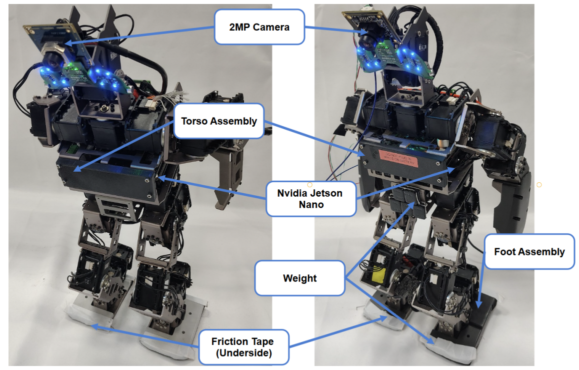

Fig. 3: Actor A (Left) & Actor B (Right) Labeled

between each wooden pole and assembly enforcement using two segments of 1 inch diameter PVC pipe cut to $15\frac{1}{2}$ inches each. Custom handle assemblies attached at the ends of each pole permit 5mm of clearance for actor grasping. Dimensions are pictured in Fig. 2.

A. Platform hardware

Executed experiments utilize modified versions of the DARwIn-OP 2 and 1 humanoid robot(s), originally developed by Robotis Co., Ltd. and the RoMeLa laboratory at Virginia Tech, which are refereed to throughout the paper as actors A and B respectively. The primary modification for both actors is substitution of the stock onboard compute unit for an Nvidia Jetson Nano, this done considerate of an inability to wirelessly communicate with a ground station and the installed operating system's lack of support for the Robot Operating System (ROS) middleware suite. Additionally, utilization of computer vision in task execution would see aid from the graphics processing unit onboard the Jetson Nano, with accuracy in locomotion further bolstered by an ability to consider detail brought about by a higher resolution image capture [13]. Image capture is accomplished by both actors through substitution of the stock camera with a 2MP USB camera, though each with differing lens and sensor specifications to refine script development methodology for future works and create computational discrepancies. Both actors maintain their stock internal IMU units, with CM-740 and CM-730 units belonging to actors A and B respectively.

Physical modifications would additionally be made to both actors in an effort to accommodate hardware substitutions and create distinctions in gait. A custom rigid assembly would be made for each actor in order to house the Jetson Nano's larger profile in comparison to the stock compute unit. Additionally, friction tape is applied to the underside of the actors' "feet" so as to mitigate error resultant from lack of physical resistance during experimentation. Actor B is appended with weights upon the "feet" (0.25 oz each) and "lower torso" (2.5 oz) sections of the body and additional custom assemblies to increase the area of contact of both "feet" with the ground (Fig. 3). These particular modifications would be made to effect actor gait, with differences in locomotion parameters permitting focus on execution of standardized tasks on non-standard platforms

B. Program Framework

The ROS middleware suite is utilized to practically communicate with the existing Robotis provided framework for DARwIn-OP. The framework itself consists primarily of kinematics solvers which guide individual motor position(s) throughout motion or action generation to ensure stable compliance to the actor's physical restrictions. Additionally, in locomotion, the controller utilizes IMU feedback to ensure balance via the application of dynamic biases to "foot" servos. Use of such within the context of this paper is limited due to complexity management cognizant of the actors' modified physical dimensions and orientational biases. ROS's publisher and subscriber interfaces are utilized over a wireless network, permitting actor-specific dynamic response(s) to relevant stimulus as it concerns the goal of a particular stage as well as coordination with the other actor in the case of collaborative stages.

A separate manager utilizes the framework for distinct "modes", each of which possess unique functions for the actor to execute and/or message types through which mode parameters may be communicated. Relevant modes include online walking mode and direct control mode which permit user-specified translational as well as rotational movement and the manipulation of individual joint positions respectively. Instantiation of the manager through an associated launch file is utilized, with custom scripts automating the cycling of modes and sending/updating of parameters both locally and between actors and the base station via ROS publishers and subscribers based on visual or IMU data.

C. Communication and Coordination

The Robotis framework and manager's use of the ROS middleware allows for wireless network-based communication as a means of actor coordination, with a base station unit separate from the humanoid actors permitting the transfer of messages and execution of relevant scripts. Select stages consider actor stability prior to action commitment to ensure proper physical and temporal coordination. This is pivotal to the sequential execution of numerous stages as is to be implemented in future works.

Physical coordination refers to the position of an actor relative to the considered rigid body, confirmation of position additionally ensuring correct positioning relative to the other actor. Temporal coordination considers the time taken for both actors to complete a given task or task segment, as execution of a successive stage prior to proper positioning invariably leads to great error(s) within overall task execution.

D. Visual Stimulus Assessment

The rigid body has segments painted an environmentally contrasting color to allow greater ease in visual discrimination, in this case the two stretcher poles. Sample images taken in a variety of lighting conditions are fed to a Gaussian mixture model which trains given a range of HSV values. A graphical representation of pixel assessment is generated (Fig. 4), with what is deemed to be a potential pixel of the stretcher occupying a particular range (shown in blue) as determined by the mentioned HSV values. A sample of the resulting color segmentation is shown (Fig. 5). Identification is translated to a look up table to ease compute strain. Computational load is additionally varied by setting unique capture resolutions of 320x240 and 640x480 for actors A and B respectively. This computational heterogeneity is intended to demonstrate variance in stage execution time and pose error relative to the stretcher. This leads to discrepancy in both physical and temporal coordination between actors which must be adjusted and/or accounted for.

A connected components algorithm based on the OpenCV library considers pixels within a visual frame determined to be part of the stretcher rigid body using the look up table, with pixels in direct proximity to one another comprising contours. Contours not meeting a threshold of number of pixels are discarded and considered visual noise. The contours meeting or exceeding the threshold are then organized into a list based on size, with the two largest contours being used as objects of interest. Camera-relative coordinates are generated via determination of the centroid of the two contours, this being the midpoint of the centers of both contours. Orientation is additionally calculated as one of the lines perpendicular to the line connecting the centers of the contours. The line utilized in this case is determined using the actor's proximity to the stretcher considerate of the dot product between the rigid body and actor headings. A single or no contour being found/labeled leads to a null output and controlled circular locomotion in attempt to find valid contours.

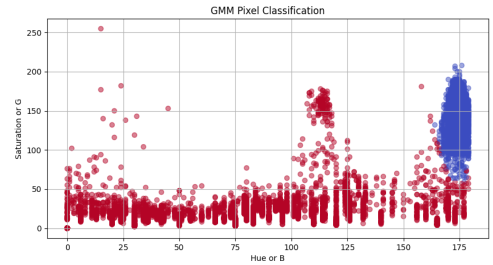

Fig. 4: Gaussian Mixture Model Training Visualization

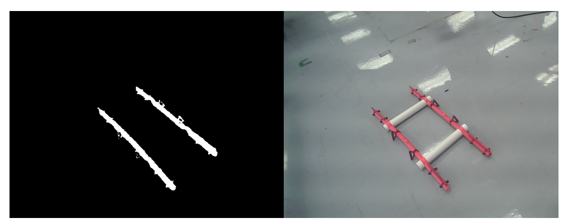

Fig. 5: Color Segmentation Demonstration

E. Search, Alignment, and Approach

Considering the humanoid actor is not initially aware of the rigid body nor in a position to make steps toward manipulation, identification and incremental alignment is the first stage considered. The "search" segment of this stage is addressed by the circular locomotion described within the visual stimulus assessment section. Movement in the "alignment" segment of the stage is dictated by a proportional-derivative controller with translational and rotational magnitude based on error of the actor's pose relative to the stretcher. PD controller constants are unique for each actor, demonstrating computational heterogeneity in a manner that effects overall gait and thus both physical and temporal coordination. Translational error is based on the position of the centroid relative to the middle of the visual frame, and the rotational error is based on the difference between the constant actor heading and the relative calculated angle of the stretcher.

In the case where two or more contours are found, the first stage's latter segment is entered wherein the actor considers the centroid and orientation of the rigid body for the purpose of alignment. The actor executes forward, backward, left, right, clockwise, or counterclockwise traversal to achieve an orientation perpendicular ($\pm 3°$) to that of the stretcher rigid body as well as a distance of 66.5 ± 1.0 cm from its centroid. The purpose of achieving this distance is to ensure the entire rigid body is within the actor's visual frame prior to potential subsequent movement reflective of practical system implementation. Prior to any traversal action taken, stability is ensured by checking that the Y axis acceleration of the actor is < 0.8m/s^2, mitigating potential failure due to postural sway magnitude or severity. Across experimental trails, actors are to maintain an initial radial distance of 75.0 ± 1.0cm and an orientation of $30° \pm 3°$ relative to the centroid rigid body's.

The approach stage sees an actor in an aligned pose take 9 steps toward the stretcher, momentarily halt traversal, and walk forward by 9 steps again until 27.0 ± 0.2cm from the rigid body's centroid. The halt in this case serves as a point of analysis for both temporal coordination and overall stability throughout the stage. This is so considering measured differences in halt time and contrast to stability throughout traversal, as well as between actors, being demonstrated by this action.

F. Grasp, Pickup, and Transport

Given both actors as being in the final approach positions described, motor position values are sent first to actors' "shoulder" joints to splay the arms and permit subsequent action without interfering with the rigid body's position. Following this, values are additionally manually sent to the "knee", "ankle", and "pelvis" joints to lower the actor's center whilst remaining balanced. This is achieved by lowering to the specified positions as long as the actor's internal IMU maintains an X acceleration value of < 2.5m/s^2. Once the positions are reached, the arms are made to move inward to grasp the rigid body's handles, and the knee, ankle, an pelvis joints are set to their original positions. The following traversal stage sees actor A walk forward and actor B walk backward, each a total of 13 steps, to stably translate the stretcher over a distance. This translation is aided in great part by the use of multiple actors, with gait analogous to that of a quadruped being adopted on account of the physical connection the stretcher provides and synchronization of steps throughout the trajectory. An MPU9050 IMU is placed at the rigid body's centroid for stability assessment.

IV. Experiment and Results

A. Search and Alignment Timing

TABLE I: Alignment Completion Time

	Time (s)	
	Actor A	***Actor B***
Trial 1	38.7452	62.6896
Trial 2	31.8481	72.5696
Trial 3	26.1944	40.1996
Trial 4	24.3625	60.3241
Trial 5	19.2485	63.8795
Trial 6	46.8345	60.1927
Trial 7	27.6725	57.1229
Trial 8	44.6535	52.6819
Trial 9	33.1214	32.0858
Trial 10	12.0387	36.3545
Mean	30.4719	53.8100

Table I presents trials wherein the actor had successfully identified and reached the desired alignment pose relative to the rigid body. The significant discrepancy between individual and mean time values indicates the extent to which differences in gait impacts temporal coordination. Such is likely resultant from the differences in capture resolution between actors, with actor A's lower resolution permitting traversal more in line with real-time as desired due to heightened frame-rate. Actor B's contrasting higher resolution leads to slower segmentation updating and thus movements which would consider an image captured earlier than desired, slowing alignment significantly. This remains consistent with known tradeoffs between image fidelity and processing latency [14]. Differences in pose error appear as well, with actor A and B possessing error ranges of $[0.6, 3.7]$cm and $[0.3, 2.8]$cm respectively, furthering discrepancy from resolution capture difference considering the smaller range of actor B aligning with its relative fidelity. Examination of small-object detection and relation between pixel footprint and detection reliability support this interpretation and align with the practice of contour thresholding as utilized [13].

PD controller values would assist in reaching what would be determined as a viable alignment pose despite discrepancies, with rotational, lateral, and forward/backward movement possessing exclusive con-

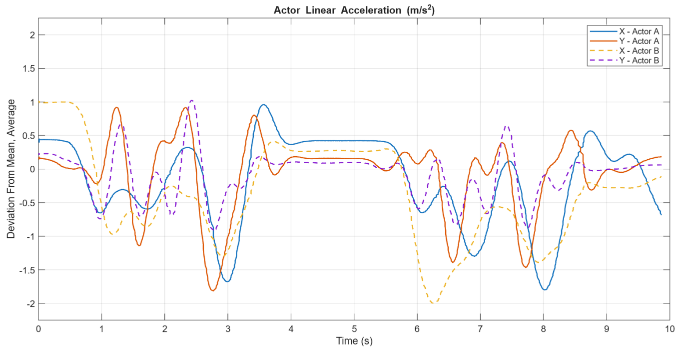

Fig. 6: Actor Acceleration During Approach

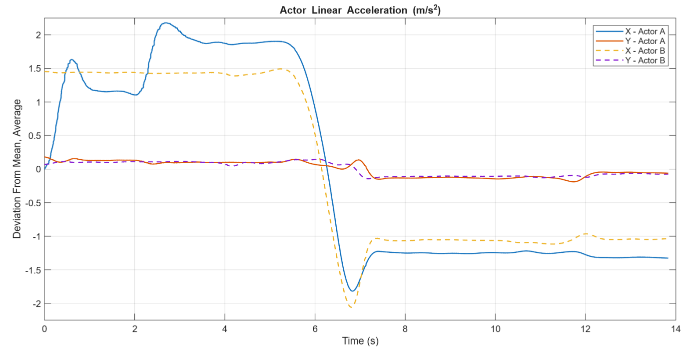

Fig. 7: Actor Acceleration During Pickup

stants. The example of rotational controller values of $[10.5, 0.05]$ and $[90, 0.6]$ for actors A and B respectively are characteristic of lateral and forward/backward value contrast as well. A near order of magnitude in difference for many corresponding constants characteristically demonstrates the extent of compensation required for viable motion, even with clear room for further error minimization in this case.

B. Approach Stability

Prior to execution, experimentation would be conducted to assure individual actor forward traversal with minimal orientation drift, requiring unique step length, step angle, lateral movement length, and foot distance values. Alternating acceleration relative to the mean throughout the 10 executed approach stage experiments characteristically demonstrate change in orientation about the relevant axes in a manner corresponding to each actor's physical sway resultant from its gait (Fig. 6). The halt segment serves to contrast the severity of said sway, with it being so that the magnitude of acceleration considerate of both axes is not large enough to destabilize directed traversal. This is indicated by the alignment of values on both the X and Y axes considerate of step frequency. Additionally, temporal coordination is demonstrated through similar times taken for the predetermined steps as well as to stabilize following the halt, demonstrating the importance of compensation in actor gait for overall stability.

C. Pickup Stability

The X-axis acceleration of both actors present while halted considerate of orientation carries over to former half of the 10 executed pickup movement stages (Fig. 7). This is expected considering bias toward stationary orientation throughout the motion, though more evident

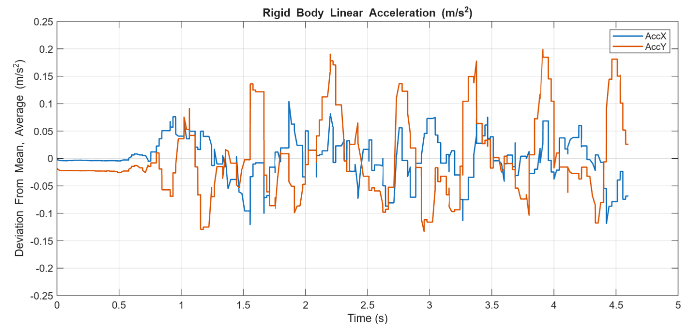

Fig. 8: Rigid Body Acceleration Throughout Traversal

considerate of the average acceleration in question lowering significantly within the latter half of the motion. This negative acceleration is primarily resultant from the formation of a virtual quadruped following the actors' physical grasping of the stretcher rigid body, with orientation about the X-axis altering for purpose of form accommodation. Considerate of successful execution, such indicates the significance of physical quadrupedic parallelism to stability. Such is seen in how alteration in orientation does not result in further motion following pickup completion. This would not be so in the case of actors performing individually wherein such must be actively compensated for as seen in the approach of both actors.

D. Rigid Body Stability

With both actors grasping the rigid body as outlined in the previous stage, 10 instances of the traversal stage had been independently executed. IMU data from the rigid body indicates relative stability with a slight trend toward increasing acceleration on the Y axis (Fig. 8). This observed trend can be attributed to orientational drift throughout the motion, with differences in lateral gait compounding over time to a point of relative significance. This is to say, although in general quadrupedic gait is overall more stable, an implemented parallel may only meaningfully adopt such characteristics given compensation in gait on part of both actors. This in regards to synchronization in not only timing as considered in this case, but orientation biases present in individual traversal. Despite this undesirable outcome, a lack of extreme instability throughout transport furthers collaboration between humanoids as a viable means for rigid body manipulation given greater means of compensation.

V. Conclusion and Future Work

This paper serves as an analysis and basis for the utilization of physically and/or computationally contrasting humanoid actors for the purpose of collaborative manipulation. Such may be extrapolated upon for operations on larger scales in terms of actor size as well as units deployed within both research and industry. The consideration of individual stages permits a modular approach to task decomposition, managing complexity as it expands and allowing differently-capable actors to operate in tandem through physical and temporal coordination.

Heterogeneity needn't be a barrier to the collaboration of humanoids, with even the compensation of individual traversal translating to fair stability as collaboration takes place. This can be seen here in the leveraging of emergent, stable dynamics from a virtual quadruped to achieve cooperative dexterity. Though a lack of complete gait compensation would lead to some drift in the case of traversal, results serve to confirm the compensation of individual actor shortcomings through collaboration This enables task execution beyond the capabilities of a single actor and further propels humanoids toward generalization.

Future work will likely seek to enhance robustness and generality of ability to compensate in the context of decomposed tasks. This would the form of real-time parameter adjustment or training for particular tasks and stages, with further sensor integration to better inform compensation parameters. Additionally considered is scaling to multiple actors for stability analysis and completion of larger-scale cooperative tasks.

VI. Acknowledgment

The authors gratefully acknowledge the contributions of Ethan Nowery, Francis Palustre, Zahir Castrejon, and Baekseok Kim at the University of Nevada, Las Vegas.

References

[1] M. Özbaltan, N. Özbaltan, H. S. Bıçakcı Yeşilkaya, M. Demir, C. Şeker, and M. Yıldırım, "Task scheduling of multiple humanoid robot manipulators by using symbolic control," *Biomimetics*, vol. 10, no. 6, 2025. [Online]. Available: https://www.mdpi.com/2313-7673/10/6/346

[2] M. Murooka, S. Nozawa, Y. Kakiuchi, K. Okada, and M. Inaba, "Whole-body pushing manipulation with contact posture planning of large and heavy object for humanoid robot," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 5682–5689.

[3] J. Pratt and R. Tedrake, *Velocity-Based Stability Margins for Fast Bipedal Walking*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 299–324. [Online]. Available: https://doi.org/10.1007/978-3-540-36119-0-14

[4] S. Dafarra, U. Pattacini, G. Romualdi, L. Rapetti, R. Grieco, K. Darvish, G. Milani, E. Valli, I. Sorrentino, P. M. Viceconte, A. Scalzo, S. Traversaro, C. Sartore, M. Elobaid, N. Guedelha, C. Herron, A. Leonessa, F. Draicchio, G. Metta, M. Maggiali, and D. Pucci, "icub3 avatar system: Enabling remote fully immersive embodiment of humanoid robots," *Science Robotics*, vol. 9, no. 86, p. eadh3834, 2024. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.adh3834

[5] I. Ha, Y. Tamura, H. Asama, J. Han, and D. W. Hong, "Development of open humanoid platform darwin-op," in *SICE Annual Conference 2011*, 2011, pp. 2178–2181.

[6] T. Sugar and V. Kumar, "Control of cooperating mobile manipulators," *IEEE Transactions on Robotics and Automation*, vol. 18, no. 1, pp. 94–103, 2002.

[7] J.-B. Yi, S. Nasrat, D. Song, J. Kim, and S.-J. Yi, "Multi-robot system for cooperative tidying up with mobile manipulators and transport agents," *Sensors*, vol. 25, no. 11, 2025. [Online]. Available: https://www.mdpi.com/1424-8220/25/11/3269

[8] Z. Xing, H. Yue, T. Zhang, W. Wu, and R. Hu, "Collision avoidance and give way of heterogeneous and variable-sized multiple mobile robots based on glued nodes," *IEEE Transactions on Automation Science and Engineering*, vol. 21, no. 3, pp. 3627–3638, 2024.

[9] A. M. Santana and A. A. Medeiros, "Cooperative path planning for a heterogeneous robotic system composed of a humanoid robot and a wheel robot," in *2008 IEEE Latin American Robotic Symposium*, 2008, pp. 117–122.

[10] S. Wen, Z. Shi, and H. Li, "Coordinated transport by dual humanoid robots using distributed model predictive control," *Biomimetics*, vol. 9, no. 6, 2024. [Online]. Available: https://www.mdpi.com/2313-7673/9/6/332

[11] Q. Zhong, Y. Li, Z. Caiming, and T. Shen, "Humanoid robot cooperative motion control based on optimal parameterization," *Frontiers in Neurorobotics*, vol. 15, 06 2021.

[12] S. G. McGill and D. D. Lee, "Cooperative humanoid stretcher manipulation and locomotion," in *2011 11th IEEE-RAS International Conference on Humanoid Robots*, 2011, pp. 429–433.

[13] Z. Wei, Y. Zou, H. Xu, and S. Wang, "Small object detection in traffic scenes for mobile robots: Challenges, strategies, and future directions," *Electronics*, vol. 14, no. 13, 2025. [Online]. Available: https://www.mdpi.com/2079-9292/14/13/2614

[14] M. Juřík, V. Šmídl, J. Kuthan, and F. Mach, "Trade-off between resolution and frame rate for visual tracking of mini-robots on planar surfaces," in *2019 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS)*, 2019, pp. 1–6.