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The GEM-C controller for Load Compensation in Object Manipulation

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Abstract— **Nowadays, robotic arms are ubiquitously employed for object manipulation across a spectrum of applications, spanning from production lines to warehouses, and encompassing both stationary and mobile robotic systems. Among the most prevalent end-effectors, used for the majority of these applications, are suction cups. The rudimentary act of grasping an object and relocating it, devoid of a cognizant awareness of the forces stemming from the object's motion and grip, can result in suboptimal and inefficient robot movements. In more dire circumstances, such negligent handling may precipitate detachment of the object from the end-effector, potentially incurring damage to either the object or the arm.**

In this paper, we build upon the advanced sensing and attaching capabilities of our suction cup MIGHTY, and introduce GEM-C, a novel Gravity, External forces and Motion Compensation controller, that constantly adapts the orientation of the suction cup so as to enhance the quality of attachment. Throughout all examined scenarios and experiments, our approach remarkably improved the robot's performance by providing the optimal end-effector pose while also reducing the stress on the motors and the overall power consumption. The derived results, clearly demonstrate the MIGHTY and GEM-C schema's potential for a wide range of demanding robotic manipulation tasks.

I. INTRODUCTION

In robotics applications, achieving precise and efficient manipulation of objects is a fundamental objective, encompassing various industries ranging from manufacturing [1] to healthcare [2], which requires a delicate interaction between mechanical dynamics, control algorithms, and environmental factors. Tasks such as assembly, material handling, and pick-and-place operations demand a complex composition of motion and forces [3] while the inherent diversity in robotic tasks, payloads and environments [4] and the presence of gravitational forces [5] impose the necessity of a fast and highly accurate load compensation mechanism.

Approaches towards the load compensation problem are mainly categorized into mechanical and software control. Mechanical load compensation is achieved with counterweights, springs, auxiliary actuators and mechanisms [6]. On the other hand, although software load compensation can improve the accuracy, it does not help to reduce the burden of the motors as mechanical compensation, but can greatly improve the control performance [7].

Another topic of research is the development of custom sensors designed for load compensation. A representative example is the six-axis force/moment (F/M) sensor with a revolutionary arrangement of 32 strain gauge sensors, developed in [8] and used in [9], where the inertia force and the inertia moment of the robot are measured and used directly for inertia force identification. The employed algorithm shortens the identification time, while also compensating for high-speed or large-load motions. Furthermore, Yao et al. [10], capitalizing on the cylindrical traction and wrist force sensors introduced in [11], developed a tandem force sensor for load estimation, utilizing the least squares method. Estimation of the force sensor's zero-point and compensating for force disturbances is carried out using Neural Networks.

Advancements in load compensation methods have yielded a range of strategies that vary in complexity, adaptability, and effectiveness, such as force-torque sensing, adaptive control algorithms, and predictive models to name a few. However, although these methods contribute to improved precision and increased safety in collaborative environments, further enhancing the potential of robotic systems, they also exhibit distinct drawbacks, inherent to each load compensation approach. For instance, predictive models offer high adaptability but may also be computationally complex [12]. Similarly, force-torque sensing provides real-time feedback but could be susceptible to sensor noise [13], while adaptive control algorithms, although enhancing flexibility, may experience convergence issues in response to varying payloads [14].

In this paper, capitalizing on the advanced attaching and sensing capabilities of our multi-functional smart suction cup MIGHTY [15], we present a novel load compensation approach for object manipulation in robotic setups. MIGHTY's embedded chambers act as force sensors which provide real-time feedback of forces and torques applied at the robot's end-effector, enabling accurate measurements of external influences, including gravitational forces, motion disturbances and load imbalances. We introduce GEM-C, a Gravity, External forces and Motion Compensation controller, to constantly monitor MIGHTY's readings and adapt the suction cup's orientation to achieve the optimal attachment pose for effective load compensation.

The validity of our approach has been extensively assessed against diverse sets of experiments in an industrial-like robotic setup. We demonstrate the unique benefits of integrating MIGHTY and GEM-C into contemporary robotic manipulators, efficiently tackling with open challenges and further enhancing the deployment of robotic suction cups. Specifically, the proposed approach manages to (i) provide real-time feedback of forces and torques applied on the robot, (ii) deliver real-time and accurate estimations about the external influences, (iii) effectively estimate the optimal pose for firm attachment and load compensation, (iv) minimize the

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forces exerted to the robot's motors and (v) reduce the overall power consumption, while also being (vi) flexible, (vii) computationally-efficient and (viii) payload-independent.

II. Methodology

In our previous work [15] we introduced MIGHTY (Fig.1), a multi-functional suction cup for object gripping and surface attachment. It's unique design, combining silicon rubbers of different hardness, provides MIGHTY with both high compliance and robustness enabling seamless attachment on any object and surface. In addition, MIGHTY is equipped with four chambers embedded in the medium hardness silicon, allowing to measure the pressure in — i.e. the applied forces on — each of the cup's corners. The chambers' pressure readings, in combination with the pressure readings inside the suction cup facilitate the accurate estimation of the forces and torque applied to the suction cup, caused either by external forces, e.g. gravitational forces and own motion of the arm, or by the object interacting with it.

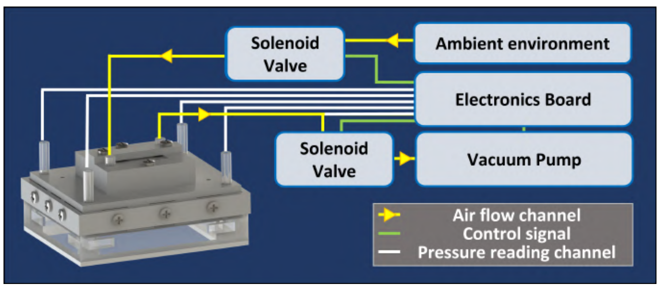


Fig. 1: Block diagram of MIGHTY [15].

A. MIGHTY Measurements

Initially, as described in [15], a calibration sequence takes place in order to convert the pressure readings of the suction cup and the embedded chambers into forces. Accordingly, the force of the vacuum F_{vac} is formulated as:

$$F_{vac} = k(P_{atm} - P_{vac})A \tag{1}$$

where P_{vac} is the pressure reading of the suction cup, P_{atm} is the pressure of the atmosphere, A is the surface area of the suction cup, and k a coefficient to cater for conversion of units.

Moreover, the force applied to the n^{th} chamber is approximated by an experimentally derived 3^{rd} degree polynomial function as:

$$F_n = C_{1,n}P_n^3 + C_{2,n}P_n^2 + C_{3,n}P_n + C_{4,n} \tag{2}$$

where $C_{i,n}$ are the fitted polynomial coefficients for chamber n and P_n is the respective pressure reading, with $n = 1,2,3,4$.

Finally, the force applied to or exerted by the suction cup, namely $F_{applied}$, is formulated as the absolute difference between the F_{vac} and the mean force reading F_{mean} (the average of the chamber force estimates):

$$F_{applied} = |F_{vac} - F_{mean}| \tag{3}$$

1) Measurements upon attachment: The above described formulations refer to force measurements regardless of MIGHTY's contact state. Naturally, for load compensation tasks, we are only interested in readings after the safe attachment of the suction cup to a surface or an object.

Let $P(n) = (x_n, y_n, z_n)$ denote an implied representation of the 3D location of each of the four corners of the suction cup's frame (accordingly, all four points are coplanar), where x_n and y_n refer to the location of the n^{th} chamber and the z_n coordinate refer to the force reading on that chamber. As illustrated in Fig. 2, let plane A represent the optimal attachment orientation without any external influence, where the force reading in all chambers equals to the vacuum force, i.e. plane A is defined by four points with $P(n) = (x_n, y_n, F_{vac}) \quad \forall \quad n = 1..4$. Also, let plane B represent the actual orientation with the z_n coordinate being the current force reading on the n^{th} chamber, i.e. plane B is defined by four points with $P'(n) = (x_n, y_n, F_n) \quad \forall \quad n = 1..4$.

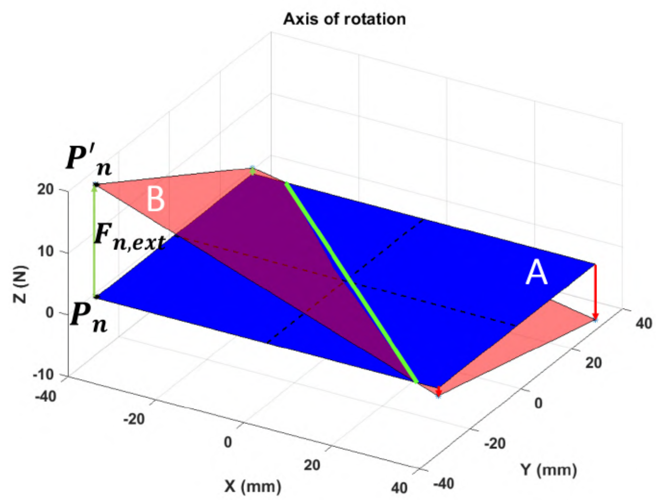


Fig. 2: Applied forces estimation.

The external force applied to the n^{th} chamber, $F_{n,ext}$, is provided by the force difference between the optimal and current state, represented by planes A and B respectively, and given by:

$$F_{n,ext} = F_n - F_{vac} \tag{4}$$

Finally, we define F_{hold}, as the holding force, applied by the suction cup, that is required for firm attachment. F_{hold} is calculated as the minimum force applied to the four chambers:

$$F_{hold} = min(F_{n,ext}) \quad \forall \quad n = 1..4 \tag{5}$$

Based on the above representation, optimal attachment is achieved when the two planes are parallel. Towards this, we introduce the GEM-C controller to compensate for load changes and ensure optimal attachment during object manipulation.

B. GEM-C controller

GEM-C stands for Gravity, External forces and Motion Compensation. The main objective of the controller is to monitor the measured forces and provide a correction signal for the orientation of the suction cup in order to keep the current plane, i.e. plane B in Fig. 2, parallel to that of the optimal state, i.e. plane A, while also maintaining the holding force above a set threshold to ensure firm attachment. This threshold, $F_{T_{hold}}$, is task- and object-dependent (e.g. manipulation of fragile objects would require higher threshold values) and is set as a percentage of the measured F_{vac}:

$$F_{T_{hold}} = t_{perc}^{hold} \cdot F_{vac} \tag{6}$$

with $t_{perc}^{hold} \in (0..1]$, since a holding force equal to zero would result into detaching from the object.

The correction procedure is run in parallel for the two axes of the plane, namely x and y. Initially, the load imbalance of each axis is calculated as the normalized applied force difference between the chambers located at the two sides of the plane:

$$F_{dif}^{a} = F_{mean}^{a,S1} - F_{mean}^{a,S2} \quad a \in \{x,y\} \tag{7}$$

where $S1$ and $S2$ denote the two sides, i.e. top-bottom for $a = x$-axis and left-right for $a = y$-axis.

Subsequently, the correction signal for each axis is formulated as:

$$s^{a} = K \cdot F_{dif}^{a} \cdot \left(1 + \frac{F_{T_{hold}} - F_{hold}}{F_{T_{hold}}}\right) \cdot \frac{F_{vac} - F_{hold}}{F_{vac}} \tag{8}$$

where K is the max speed signal and F_{dif}^{a} is the estimated force difference between the opposite sides of the axis. The two remaining terms, serve as signal reinforcement, by adjusting the correction speed, based on the firmness of attachment (for the first term) and the load imbalance (for the second term).

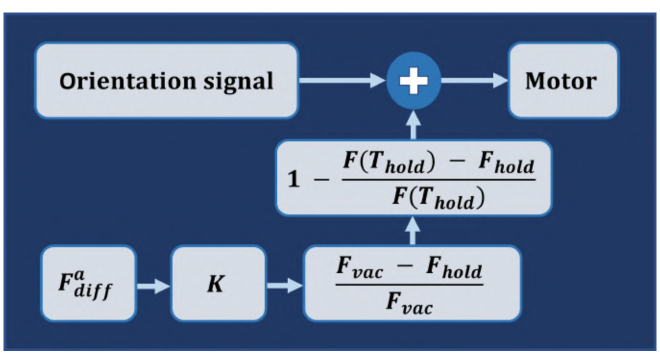


Fig. 3: GEM-C controller scheme.

Finally, as illustrated in Fig. 3, the correction signal is added to the desired orientation signal of each axis of the suction cup and provided to the corresponding motor for pose adjustments that maximize the holding force on the suction cup while also minimizing the torque between the suction cup and the attached object.

The employment of the GEM-C controller equips MIGHTY with advanced load compensation capabilities, providing fast and accurate holding force estimations based on force distribution and constantly adjusting the orientation of the suction cup in order to minimize the applied torque and reduce the overall power consumption as a result of the minimized effort needed by the actuators to manipulate the attached object.

III. GEM-C Evaluation

In order to assess the performance of the proposed system, we designed diverse sets of experiments utilizing the MIGHTY suction cup in various conditions and configurations as an end-effector. Specifically, four evaluation scenarios where configured to evaluate the quality of: gravitational forces compensation, rapid change of object's center of mass compensation, moment of inertia compensation and external forces compensation. For a quantitative representation of GEM-C, all experiments were repeated with and without employing the GEM-C controller and the corresponding performance was assessed against three criteria: loss of holding force, torque and forces applied to the motors and overall power consumption..

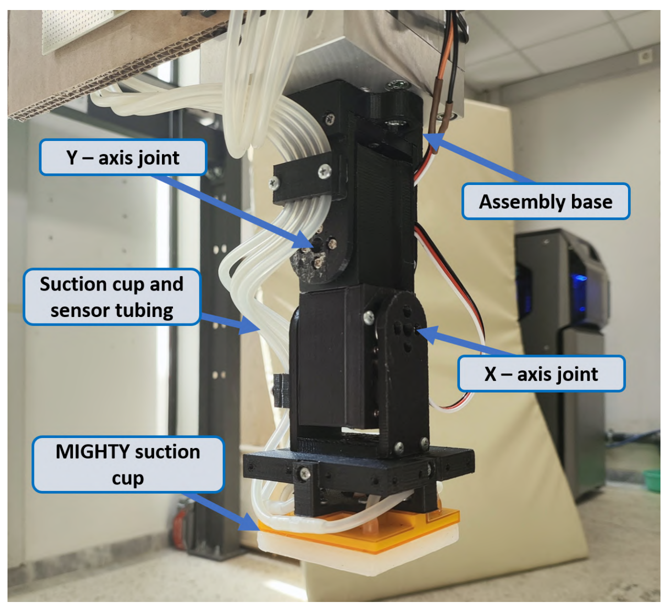


Fig. 4: Experimental wrist joint.

For the purposes of this evaluation, an experimental apparatus was created, consisting of the MIGHTY suction cup and a two degrees of freedom wrist joint, as shown in Fig. 4. The corresponding control unit, depicted in Fig. 5, consists of three main components, the MIGHTY suction cup control board (WaveShare general robotics board), the wrist joint control board (Teensy 4.0) and an assembly composed by two solenoid valves and a vacuum pump (BOXER 20KD Diaphragm Pump). MIGHTY suction cup control board is tasked with monitoring all of MIGHTY's pressure sensors

(Bosch bmp280), operating the vacuum pump and solenoids, while also interfacing with the main computer. On the other hand, the wrist joint control board is used to operate the two servo motors of the wrist joint, while monitoring their speed, position, voltage, current and effort. In order to provide a relevant environment for testing GEM-C's load compensation in robotic object manipulation, the experimental apparatus was mounted on a Cartesian robot, consisting of four Festo linear axes, two for the X axis, one for the Y axis and one for the Z axis. The resulting experimental setup is depicted in Fig. 6, while Fig. 7 shows representative examples for each scenario configuration.

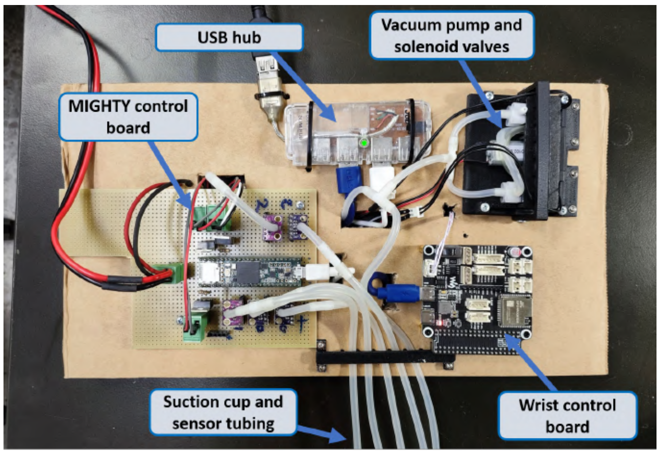


Fig. 5: MIGHTY - Wrist Joint control unit.

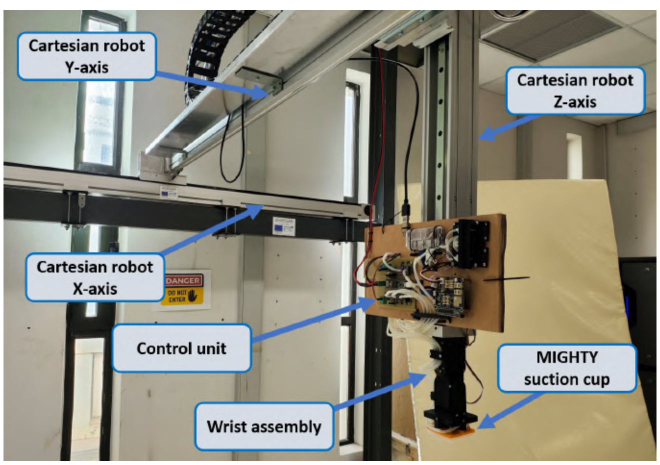


Fig. 6: Industrial-like experimental setup with MIGHTY, the wrist joint, the wrist control unit and the Cartesian robot.

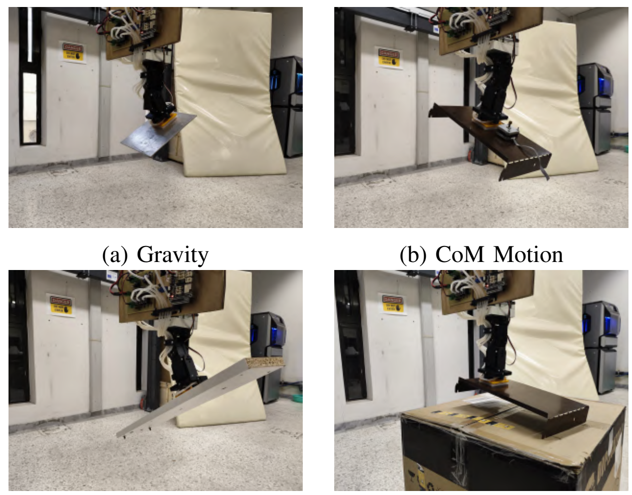
A. Evaluation Scenarios

1) Gravity compensation: The first scenario aims at assessing the ability of the GEM-C controller to compensate for the effect of gravity during object lifting. Throughout the experiments, MIGHTY is placed above a test object and attached to it at varying locations, followed by a slow lift up, of the experimental apparatus and the object, by the Cartesian robot, i.e. vertical motion along its z-axis.

During the lifting movement, GEM-C is tasked with controlling the wrist orientation in such way as that the holding force remains vertical to the plane of the suction cup.

2) Moving center of mass compensation: The second scenario entails the assessment of the effectiveness of our system to compensate for arbitrary movements of the object's center of mass (CoM) during object manipulation. In this setup, MIGHTY is attached to a metal plate, while, magnets of known size and weight are gradually attached to the plate's surface, in order to simulate the object's COM change.

In this series of experiments, the controller aims at adjusting the pose of the suction cup in order to balance out the pressure within the four chambers, or, in other words, to make the current cup plane parallel to the optimal one, as of in the example illustrated in Fig. 2.



(a) Gravity (b) CoM Motion

(c) Inertia (d) External

Fig. 7: Illustrative examples of different scenario configurations.

3) Moment of inertia compensation: The experiments belonging in the third scenario aim at evaluating GEM-C performance under rapid robot movements. For this setup, MIGHTY is repetitively attached, at arbitrary locations, to an unknown object while the Cartesian robot is freely moving along its x and y-axis at varying speeds and accelerations.

Similarly to the previous experiments, the GEM-C controller is responsible for compensating for the forces applied to the object and, thus, to the cup due to the moment of inertia. This is achieved by adapting MIGHTY's orientation to maximize the cup's holding force, while also adjusting the speed of the apparatus motors according to the perceived speed of load changes.

B. Experimental Results

Table III-A.4 summarizes the results of the GEM-C evaluation under all four scenarios. The system's performance, with and without the GEM-C controller, was assessed with respect to the defined criteria -namely holding force loss, applied torque and forces to the motors and power

TABLE I: Quantitative evaluation of the GEM-C performance.

	Loss of Holding Force (N)		**Power Consumption (mW)**			**Torque applied (Nm)**		**Force difference (%)**		
	max	average	min	max	average	max	average	min	max	average
GEM-C Active	6.34	2.62	12	76	27.78	8.10	2.84	6	26	17
GEM-C Inactive	58.74	19.62	24	60	30.94	27.97	15.99	9	73	42
difference	**52.40**	**17.00**	**12**	**-16**	**3.16**	**19.87**	**13.15**	**3**	**47**	**25**

4) External forces compensation: For the last scenario, we aimed at evaluating the GEM-C performance during object manipulation under external forces. In this setup, MIGHTY is purposefully attached to an object in such a way so that its CoM is aligned with the object's CoM, in order to account only for the compensation of external forces that are applied to the attached object. For simulating the desired behavior, forces of varying magnitude and direction are manually applied on pre-defined locations of the object.

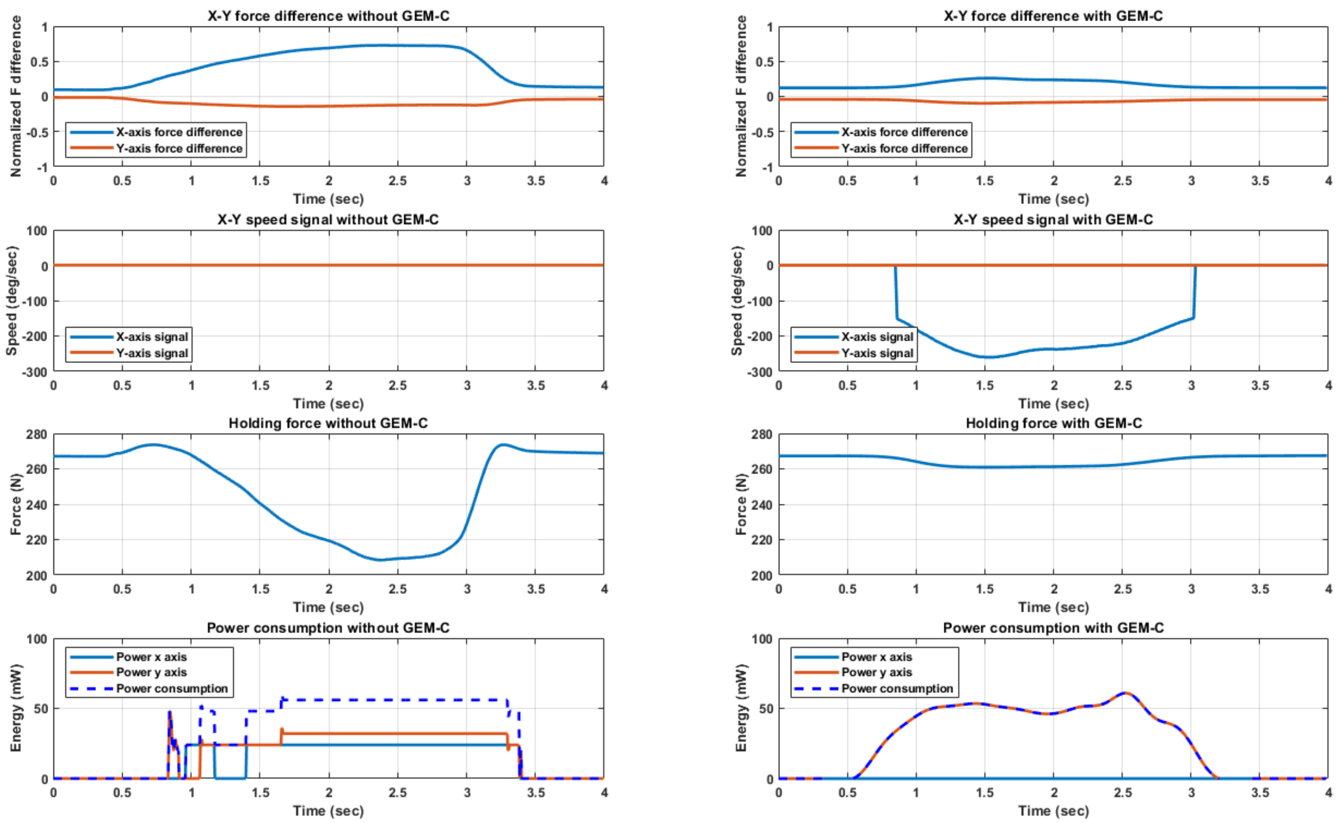


Fig. 8: Qualitative evaluation of the GEM-C performance.

consumption- while the provided values represent the average values across all experiments of the corresponding scenario.

Evidently, the employment of GEM-C significantly enhanced the robot's performance for all scenarios and experiments against all criteria, by providing the optimal attachment orientation and maximizing the holding force of the suction cup, by efficiently compensating for all types of external disturbances and load imbalances, while also minimizing the effort and, thus, the power consumption of the wrist motors. Overall, across all scenarios, GEM-C achieved impressive results and managed to reduce the average loss of holding force by 17 N, reduce the average applied torque and force differences by 13.15 Nm and 25%, respectively, while also reduced the average power consumption of the experimental system by 3.16 mW.

The beneficial impact of GEM-C is also illustrated in Fig. 8, which includes representative plots of the acquired readings and measurements, depicting the overall operation of our experimental apparatus during object manipulation, and, specifically, during the gravity compensation experiments. The plots on the left side of the figure refer to measurements acquired while GEM-C was inactive, while those on the right side refer to measurements while GEM-C was active.

Top row depicts the measured difference of applied forces F^{a}_{dif} for the x- and y-axis of the suction cup, highlighting the minimized load imbalance that is achieved by the GEM-C controller, while the second row shows the corresponding correction signal, namely s^a, that GEM-C sent to the motors as an immediate response to this load imbalance. Naturally, since on the left side GEM-C was inactive, no correction signal was sent.

Finally, the estimated holding force of the suction cup and the overall power consumption of the experimental apparatus are shown in the third and bottom rows of Fig. 8, respectively. Again, the provided plots clearly demonstrate the performance improvement that is achieved by GEM-C. On one hand the holding force, i.e. the firmness of attachment, remained, practically, unaffected by the external forces. On the other hand, although limited, the reduction in power consumption is highly noteworthy if we consider the setup and time frame of the presented example, further highlighting the potential of GEM-C in long-term object manipulation tasks.

IV. Discussion

In this paper, we capitalized on the sensing and attachment capabilities of the suction cup MIGHTY in order to address the problem of load compensation in robotic object manipulation tasks. To this end, we introduced GEM-C, a Gravity External forces and Motion Compensation controller which aims at constantly monitoring the readings and measurements of MIGHTY and provide with the optimal pose of the suction cup, so as to maximize the firmness of attachment, minimize the torques applied to the robot's motors and reduce the overall power consumption.

The validity and effectiveness of the proposed approach has been thoroughly evaluated against four sets of experiments: gravity compensation, moving center of mass compensation, moment of inertia compensation and external forces compensation. For the purposes of the evaluation, MIGHTY was mounted on an experimental wrist joint, acting as an end-effector of a 3-DoF Cartesian robot, simulating an industrial-like environment. Across all scenarios and experiments, GEM-C achieved remarkable performance with respect to the examined criteria, showcasing its efficiency and effectiveness and its beneficial impact on robotic load compensation tasks.

Although GEM-C successfully copes with a series of challenges in robotic manipulation tasks, there still remaining open issues, or opportunities, that need to be carefully considered in order to enhance the MIGHTY's and GEM-C's performance, portability and scalability. Towards this end, our immediate steps entail (a) the development of a self-calibration mechanism that will further improve the controller's accuracy and reduce operation times, (b) the integration of the wrist joint and its control parts onto MIGHTY in a compact way to increase portability and readiness of use, and (c) to account for the whole robotic system and provide the optimal pose for all involved motors in the kinematic chain.

In addition to the capabilities already assessed, there are more to be explored, including real-time mechanical diagnostics for the robot on use, vibration detection, surface roughness and cracks detection, and haptic sensing, to mention a few. In fact, the revolutionary design of MIGHTY, in combination with the advanced capabilities of GEM-C, significantly enhances the applicability of our system, not only addressing object manipulation tasks but also a wide variety of robotic applications, ranging from production lines and warehouses to autonomous infrastructure monitoring and maintenance, or even autonomous climbing robots.

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