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Dynamically Evaluated Gravity Compensation for the RAVEN Surgical Robot

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Abstract— **Using an accelerometer on the base of a robot, it is possible to calculate the torque required from each actuator in order to maintain a known pose regardless of base orientation with respect to the direction or magnitude of gravity. A simple and novel method has been developed and implemented for overcoming gravity induced torques on the RAVEN™surgical research robot. This innovation will allow for accurate control of serial robot manipulators with re-orientable bases or for those operating in non-stationary environments such as boats, space stations, or moving vehicles.**

I. INTRODUCTION

One of the most lauded and world-changing applications for surgical robots is their potential for use in remote locations without specialized surgeons [1]. One can easily imagine the utility of a highly automated or teleoperated mobile operating room in underdeveloped areas, battlefields or areas of natural disaster. In such cases, these operating rooms may be on a rocking hospital boat or in a large trailer on uneven terrain. These dynamic and unpredictable applications introduce challenges in the low-level control of surgical robots. This project aims to provide a solution to the control of a surgical robot with an unknown or changing orientation with respect to gravity.

Gravitational loads on robotic manipulators often present a large, non-linear contribution to static and dynamic control. In many cases, this load can be calculated and compensated for when the positions of the robot links are known with respect to a base frame. Traditionally this base frame is stationary with respect to gravity, such as an industrial robot bolted to a factory floor or a monolithic surgical robot with a heavy, fixed base column. This project aims to provide similar compensation in cases where the base cannot be assumed to be in a fixed orientation with respect to gravity; in such cases as a robotic arm attached to a mobile reconnaissance platform or a surgical robot on an aircraft carrier. It is proposed that actively evaluated gravity vector compensation will greatly improve the control performance of a serial robotic manipulator with a non-stationary base.

A. RAVEN Surgical Research Robot

The RAVEN surgical research robot is an open source system developed at the University of Washington and the University of California Santa Cruz as a means of researching and innovating in the field of surgical robotics. After developing and rigorously testing the limits RAVEN I [2], development of RAVEN II began as a common research platform for research labs across the US. In 2012, the first RAVEN II systems were shipped to seven top research institutions as the inaugural members of the RAVEN community [3]. With a common platform built on software standards, the RAVEN community is well suited to collaborating and innovating in the space of surgical robotics and related fields.

The RAVEN II is a compact, cable-driven mechanism with 3 spherical joints and a 4 Degree of Freedom tool. The spherical joints mechanically constrain robot motion to a virtual center, which is a desirable characteristic for minimally invasive surgical robots since they must enter the body through a key-hole incision. Figure 1 shows the RAVEN II arms and controller.

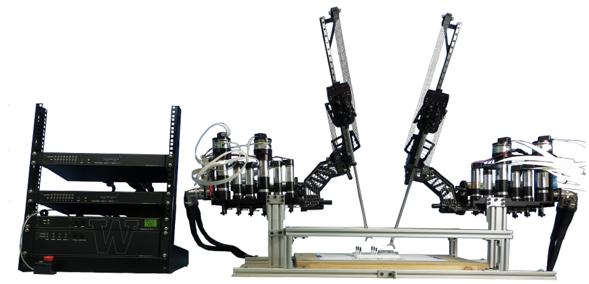

Fig. 1: The RAVEN II surgical research robot system developed at the University of Washington and University of California Santa Cruz. On the left are the control electronics and emergency stop switch.

B. Control with Gravity Compensation

The most common form of low-level control in robotics applications is the Proportional Integral Derivative (PID) controller or some combination of those terms. This family of controllers determine motor torques using the error between the robot's current position and its desired position as the input. Since the early 1990s, it has been known that PID and PD controllers with a gravity compensation term are stable about a reference position for any rigid manipulator [4]. However, it has not yet been proven that PID controllers can be globally stable in robots with elastic joints. Tomei has shown that PD control with a gravity compensated term at the desired configuration is enough to prove global stability about this reference position, but accurate knowledge of

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RAVEN is a registered trademark of the University of Washington and Applied Dexterity gravitational effects is necessary for accurate positioning of a robot with elastic joints.

Another challenge to controlling robots like the RAVEN is the elasticity between the joints due to the use of cables. Alessandro De Luca et al. has contributed a significant amount to the theory of controlling elastically jointed robots. In [5], he points out that exotic, complex control solutions are available for tracking tasks such as linearizing and decoupling nonlinear feedback, an integral manifold approach based on perturbation of the dynamic model, or adaptive, neural network control. He continues to survey the PD plus gravity compensation approaches since [4] first proved that the gravity compensation of a desired position was sufficient for regulation task stability, with the gravity term $g(q_d)$ where q is the robot pose and q_d is the desired robot pose. This approach is termed a constant gravity compensation term. A nonlinear gravity compensation scheme requires evaluating the required gravity torques for the current position of the robot during its movement, $g(q)$. Finally, gravity compensation can take the form of an on-line term with torques calculated from the motor positions when it is impractical to sense joint angles, $g(\theta)$. With elasticity between the motors and the joints, on-line gravity compensation will naturally lead to steady state errors because the actual pose of the links is not compensated for. The contribution of [5] is a PD control law with gravity compensation calculated with a new variable $g(\tilde{\theta})$, a gravity-biased motor position that uses a model of joint elasticity to provide a more accurate description of the robot pose. This technique is shown to have smoother control transients in the motor torques and provides a larger range of feasible PD gains over the PD controller with constant gravity compensation proposed in [4].

C. Dynamics of Robots on Moving Bases

The Mitsubishi PA10-6CE has been used in several investigations into the dynamics of robotic manipulators on moving bases. A model was derived for arbitrary 6-DOF disturbances and implemented for the robot by Wronka and Dunnigan with a 2 DOF rotary base [6]. The derivation assumes that the characteristics of the moving platform are known and it is assumed that the motion of the manipulator has no significant influence on the motion of the base. The Lagrange-Euler method is used for the full dynamic model. This technique uses the total energy of the system and inherently includes a gravity term in the calculation of potential energy. The main goal of the work was to develop an accurate model of the robot for simulation purposes and they found that the model is accurate and the inclusion of a gravity term in the model significantly improves its performance for use in future work with the robot. Sadraei and Moghaddam derive both a Lagrange-Euler model and a Newton-Euler model of the PA10-6CE and simulate the rocking of a ship to test computational performance of the models [7].

In parallel with their modeling efforts, Dunnigan and Wronka compared the performance of a wide variety of model-based and adaptive control methods for a robot on a moving base in [8]. This study used the PA10 robot on a 6 DOF base and compared the control methods with no base motion sensor, an angular orientation sensor, and an accelerometer. Dunnigan found that joint-tracking performance was greatly improved in all controllers with the inclinometer, further improved with an accelerometer, and performed best with an adaptive gravity compensation term. The researchers concluded that not only could the adaptive term compensate for changing gravity induced loads, it could also compensate for unmodeled effects such as harmonic drive compliance.

In 1999, Iagnemma et al. constructed a low-cost model similar to the JPL Lightweight Survivable Rover with a 6-wheeled rocker-bogie system and a 3 DOF manipulation arm with several end effectors [9]. Global torques on the manipulator were measured with a 6-DOF force-torque sensor at the base of the arm and a gravity compensation term was used to subtract the contribution of gravity from the reading. Instead of using gravity compensation as a term for motor torque output, it is used as a term for compensating torque feedback. It is mentioned that the gravity term is dependent on the orientation of the base, which is measured by an accelerometer.

D. Surgical Robots, Teleoperation, and Haptic Devices

A recent study investigated the effects of gravity compensation of a haptic master controller under external accelerations [10]. In order to compensate for the biodynamic feedthrough of the limbs of the user, acceleration dependent damping coefficients and mass parameters were used in the control of the Force Dimension omega.7 haptic controllers. Preliminary results from experiments in an elevator and moving van showed increased user performance over constant damping. The tests culminated in a microgravity and variable gravity experiment in which surgeons were asked to perform suturing tasks with the devices with a teleoperated SRI international M7 robot while on board the NASA C-9 airborne parabolic laboratory. Results showed that the variable acceleration compensation improved performance of the user during constant and variable gravity, but did not appear to help in zero g.

II. Project Goals

In the reviewed literature, only a few studies have mentioned the effects of changing base orientation and even fewer have evaluated the use of sensors to study or compensate for these effects. This project proposes to integrate sensor data into the calculation of gravity compensation torques and use this term to implement a PD plus gravity compensation controller. Moreover, this project will study the performance of a controller that is able to respond to sensed relative gravity and acceleration data, deemed a PD plus dynamic gravity compensation controller, or PD+DG for short. This control and a standard static gravity vector compensation controller (PD+SG) will be implemented on the RAVEN surgical robot for controller performance evaluation. The sections that follow describe the analysis of the problem,

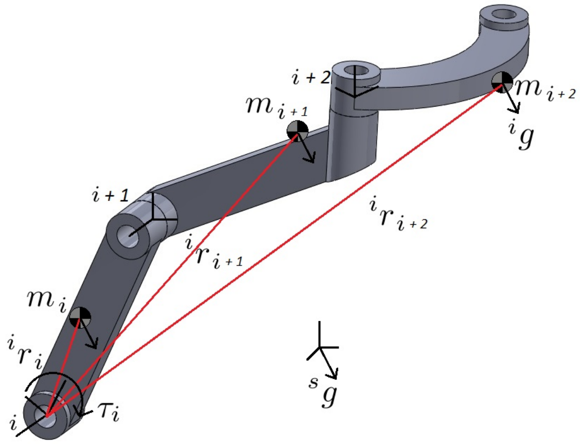

Fig. 2: A generalized model of a serial robot. By representing the center of mass of each successive link in the frame of link i, it is possible to calculate the required gravity compensation torque for joint i.

approach to the solution, and a discussion of experimental results on the RAVEN.

III. ANALYSIS

A method for solving for gravity torques on each gross-positioning actuator was developed which allows for variable acceleration vectors, center of mass (COM) parameters, and kinematic details.

As shown in Figure 2, the torque on each joint is determined by summing the torque contributions of each successive link. This is easily accomplished using forward kinematics transformations to represent each COM and the acceleration vector in the frame of the joint being considered. It is assumed that all frames are defined using the Denavit-Hartenberg convention. With this assumption, the force or torque required to compensate for the contribution of external accelerations is merely the negative z-component of the calculated imposed force or torque. For rotary joint i, the gravity compensation torque is

$$\tau_i = -{}^i\hat{z} \cdot \sum_{k=i}^{N} {}^i r_k \times {}^i g * m_k \tag{1}$$

where ${}^i\hat{z}$ is the unit z vector of frame i ($[0\,0\,1]^T$), N is the number of links, ${}^i r_k$ is the vector to the center of mass of link k in frame i, ${}^i g$ is the external acceleration represented in frame i, and m_k is the mass of link k. The following equation is used to find the representation of gravity in frame i:

$${}^i g = {}^i_s T \, {}^s g \tag{2}$$

where s is the frame of the accelerometer.

The gravity compensation force for a prismatic joint is

$$f_i = -{}^i\hat{z} \cdot \sum_{k=i}^{n} {}^i g * m_k \tag{3}$$

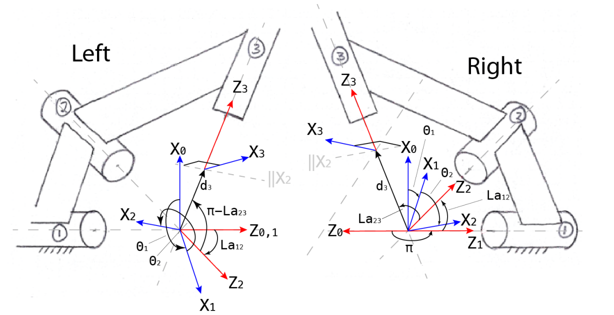

Fig. 3: The base and gross positioning frames of the RAVEN II robot as described in [11].

High level implementation of these equations with the help of available kinematics transforms makes it easy to use a variable value for ${}^s g$. By incorporating acceleration data from a sensor, this gravity compensation method can be easily used to implement a dynamic gravity compensation term.

Center of mass locations for the RAVEN robot were derived from CAD models of each link assembly. Link assembly masses were directly measured during the latest round of RAVEN construction. The forward kinematics for RAVEN are analysed in [11]. Figure 3 shows the first three link frames used in the analysis.

IV. METHODS

A. System Architecture

In order to incorporate a new acceleration sensing modality to the RAVEN system, a sensing subsystem was designed to communicate with the main RAVEN control via ROS networking capabilities. A high-level system diagram can be seen in Figure 4. A Bosch BMA180 accelerometer breakout board (sparkfun.com) was used to sense the external accelerations. An Arduino was used to communicate with the sensor. The `rosserial` package was used on a netbook computer connected to the Arduino via USB to allow ROS messages to be generated on the Arduino at 100 Hz. Due to data type limitations of the `rosserial` package, a separate node was implemented on the netbook to create a `gravity` message with acceleration vector and magnitude data. The architecture of the sensing subsystem can be seen in Figure 5.

The RAVEN software was updated to subscribe to the `gravity` message and the high-level gravity compensation calculations were implemented. Since the functionality for retrieving forward kinematics transformations was already available, implementing the algorithm in an easy to read manner was straightforward and allowed for variability in the gravity vector and other parameters. If there is no `gravity` topic published at start-up, a gravity vector for the nominally level base orientation is assumed. However, if the `gravity` topic is interrupted, the program will continue to use the last published value.

Feedforward PD plus gravity compensation control was implemented as seen in Figure 6. The gravity compensation torque is a function of the current gravity (or acceleration)

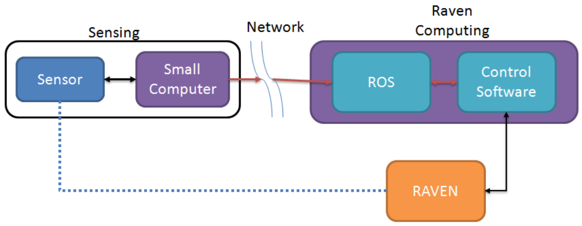

Fig. 4: High level architecture of proposed sensor integration system.

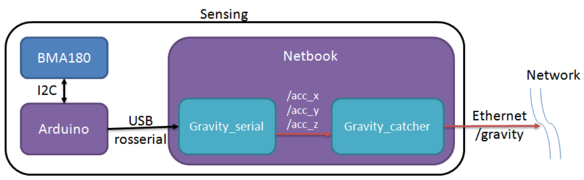

Fig. 5: The sensing subsystem consisting of an accelerometer, Arduino, and netbook computer.

vector and the sensed pose of the robot. The gravity torque is added to the standard PD term. Additionally, the gravity compensation term can be used by itself for a passive pose compensator. This compensator mode was used to subjectively validate the gravity compensation term by placing it in a variety of poses at a variety of base orientations. The compensation terms were known to be correct if the robot held the pose without drifting.

B. *Experimentation*

The efficacy and performance of the PD+DG controller were tested under three conditions. In each condition, the PD+DG controller was compared to a PD+SG controller as described above. In order to not confound the effects of gravity compensation, the PD gains were those used in the standard RAVEN PD control and were the same in each controller.

First, the controllers were validated against a standard PD-only controller at a variety of robot poses and base orientations. Each controller was used to maintain a static pose at increments along the range of the first joint. When

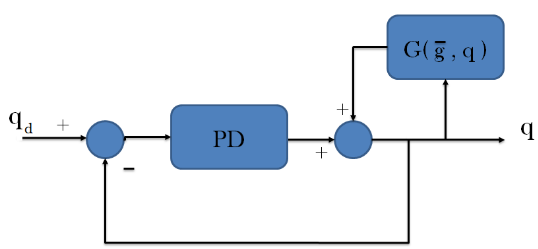

Fig. 6: A diagram of the PD+DG controller, in which a desired orientation q_d is achieved through negative position feedback (from the robot pose q) into a PD term which is summed with a feed-forward gravity compensation term G. The function G is dependent on the robot pose q and the gravity vector $\bar{g}$.

using the PD only controller, the gravity compensation terms were calculated and compared to the applied torque. These values were expected to be equal. The base angles tested were about the Z_0 axis in Figure 3 and ranged from 0 to 20 degrees.

Next, the controller's trajectory tracking performance was tested with a test trajectory at the same range of increasing base angles. The trajectory consisted of sequential sinusoidal motions along each Cartesian direction in the robot workspace. The trajectory had an amplitude of 3.1 inches and a period of 4 seconds for each direction and was observed for two full cycles in each test. The trajectory was sent as a series of workspace increments from the haptic master software at 1000 Hz.

Finally, trajectory performance was tested with continuously changing base conditions. In this trajectory, the base was rocked by hand between base angles of ten and twenty degrees at a frequency of 1 Hz. This was accomplished using a pair of lever arms with angle markings, so that an experimenter could rock the robot in time with a 120 beat per minute signal generated by the Slick Metronome Android application.

Two metrics were used to evaluate control performance. For trajectory following performance, the root mean square (RMS) joint error was used. This was calculated as the difference between the desired joint position and the joint position sensed at the motor encoders. Modeling accuracy was evaluated by calculating the RMS effort of the PD term as a percentage of the RMS of the total control torque throughout the observed trajectory. In static or semi-static poses, this PD percentage should be very close to zero when gravity compensation is enabled, as the gravity compensation term should provide zero steady state error. Thus, this metric can be useful in observing how accurate the compensation model is. In trajectory tracking tasks, PD percentage can indicate how helpful the gravity compensation term is. For instance, if the PD percentage is much greater than 100%, then the PD spends a significant effort fighting the gravity compensation term, which indicates that gravity compensation is reducing tracking performance.

V. RESULTS

A. *Controller Validation*

Initial validation testing was designed to ensure that the calculated values of the gravity terms are correct. When the robot base was at its nominal horizontal orientation, both the dynamic gravity and static gravity calculated terms matched the PD torque values at a variety of static tested positions. As expected, the SG term became less accurate at increasing base angles. Figure 8 shows the divergence of the two gravity compensation terms.

Also as expected, the PD+DG performed more accurately with changing base angles than the PD+SG and PD-only controllers. The DG control term accounted for nearly all of the total control torque and the PD did very little correcting since the PD exerted nearly zero torque at almost all times and the sum of the PD and DG terms followed very closely

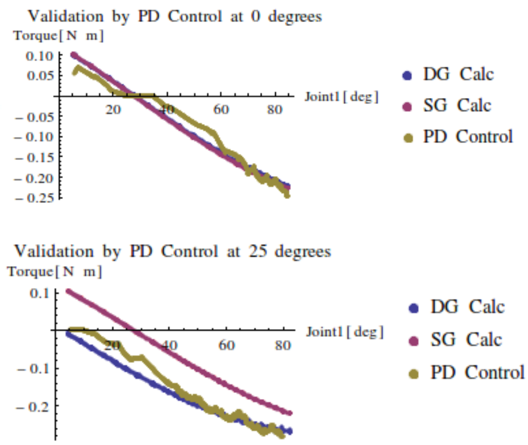

Fig. 7: Calculated gravity compensation terms compared to PD torques at base angles of 0 and 25 degrees during validation poses.

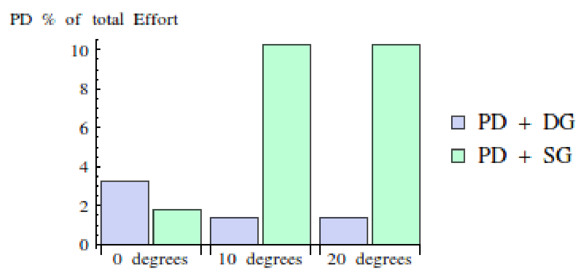

Fig. 8: PD term as a percentage of RMS torque in gravity compensated controllers at increasing base angles during validation poses.

to the DG term. However, the PD+SG controller required more effort from the PD term in order to hold a pose with increasing base angles. The stark contrast in performance can be seen in Figure 8, which shows the RMS value of the PD term as a percentage of total RMS torque throughout the trajectory. This figure implies that the PD term needed to contribute more overall effort due to inaccuracies in the gravity compensation in the PD + SG controller at non-horizontal angles.

Operating with only a DG term and no PD, the robot passively held any new position manually imposed by the experimenter. The majority of the resistance to motion in this mode was apparently motor inertia and cable friction terms. This effect is seen at all tested base orientations for the DG term (even upside-down), but only at or near horizontal with the SG term. Unlike the DG only controller, when the SG only controlled robot was tipped more than a few degrees the robot will drift due to the error in compensation.

B. *Trajectory Following with Static Base Angles*

As expected from the literature, in our experiments gravity compensation did help tracking error. Figure 9 shows that joint tracking error was improved by gravity compensation for the first joint, about which the base was tilted. At a base angle of 20 degrees, the PD+DG controller's RMS

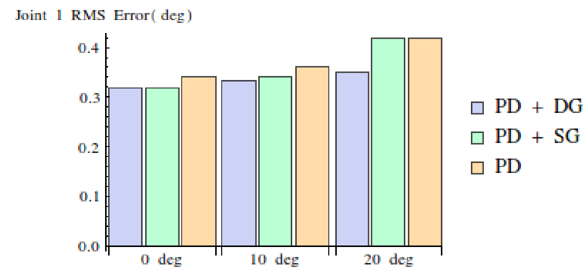

Fig. 9: RMS joint angle errors in degrees for each controller at each angle.

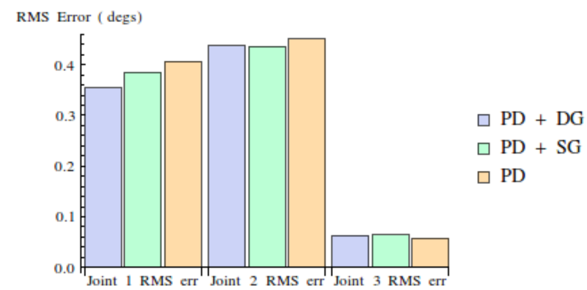

Fig. 10: RMS of joint angle error for the three controllers during autonomous trajectory with rocking base.

joint 1 error was around 12% less than the error of the PD-only controller. Tracking error with the PD+SG controller increased at 20 degrees. At 20 degrees, the inaccuracy of the gravity compensation term in the PD+SG controller negated any improvements that it may have imparted. Joint 3 had higher errors with gravity compensated control over PD-only control.

C. *Trajectory Following with Rocking Base*

Under constantly varying base angles, the gravity compensated controllers showed little collective effect on Cartesian tracking performance. However, Figure 10 shows that joint 1 tracking performance increases by the same 12% as in the static base angle tests.

VI. DISCUSSION

Our experiments validated the accuracy of a gravity torque model of the RAVEN robot and showed that sensing the base acceleration vector in real-time could be used to compensate for base motion in addition to gravity.

Using a real-time value for the gravity vector in gravity compensation calculation decreased the PD effort in regulation and tracking tasks in applications where the robot base pose is adjustable or subject to movement during operation. This was due to the improved accuracy of computing gravity loads as demonstrated in Figure 8. This figure demonstrates that assuming a constant gravity vector required the PD term to "fight" the inaccurate gravity term in order to achieve the desired state.

Dynamic gravity compensation showed the same improvements over static gravity compensation with a constantly varying base angle as with statically increasing base angles.

Joint 1 tracking performance improved with both types of gravity compensation we implemented. This was likely due to this joint having the highest imposed gravity torques since it carries the mass of all subsequent links. This joint also acts in parallel with the imposed rotations in testing, so it has the most to gain from an accurate dynamic gravity compensation term in these tests. Not only was the performance increased with changing gravity direction, but also with changes in acceleration magnitude.

Joint 3 performance, however, did not show significant improvements. This may be due to the different nature of compensating for linear rails and the high degree of cable coupling associated with the tool spindles on the tool carriage.

VII. CONCLUSIONS AND FUTURE WORK

A feedforward dynamic gravity compensation term has been shown to improve control performance when added to a standard PD controller on the RAVEN robot. A practical high-level algorithm was implemented that takes advantage of low cost sensors to generalize gravity compensation to base motion compensation.

Further studies can focus on other aspects of control performance under varying base conditions, such as perturbations or sustained accelerations. The step-response of the PD+DG controller under these conditions would provide an interesting study. Furthermore, a study of the frequency response of the system with the PD+DG controller could show a case in which specific perturbations of the base could create a positive feedback instability between the robot motion and the accelerometer.

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