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Internal Posture Sensing for a Flexible Frame Modular Mobile Robot

Roy Merrell and Mark A. Minor
Department of Mechanical Engineering
University of Utah
Salt Lake City, UT 84112
minor@mech.utah.edu

Abstract - **A sensor fusion algorithm for flexible framed modular mobile robots is presented in this paper. This algorithm uses traditional Kalman filters and rigid axle kinematic models to predict the global posture of each axle. A Covariance Intersection filter is then proposed for fusing these axle modules using data provided by the compliant frame module. Modeling and instrumentation of the compliant frame module is the remaining focus. The instrumented frame is required to estimate the relative posture of the axles as well as the force components and moment that the beam exerts on each axle. These estimates must also be valid for large deflections in order to accommodate a reasonable turning radius. To accomplish these goals the beam equations are derived. A linear interpolation of the strain gauge data is used to calculate posture, force, and moment estimates. Experimental results show that the frame module can yield accurate relative posture estimates for large deflection.**

1. INTRODUCTION

A new breed of wheeled mobile robotic systems is the subject this research: compliant framed modular mobile robots, Figure 1. The concept is unique in two ways. First, it uses a novel yet simple structure to provide suspension and highly controllable steering capability to mobile robots without adding any additional hardware to the system. This is accomplished by using flexible frame elements to couple rigid differentially steered axles. In this study, the frame element provides compliant roll and yaw between the axles. Roll provides suspension capability to the system by allowing the axles to deflect in order to accommodate uneven terrain, and yaw allows the axles to independently change heading for advanced steering capability. Steering and maneuvering of the system are thus accomplished via coordinated control of the axles in order to achieve a desired mobility task such as path following or stabilization about a point. Since each axle can be steered independently, the system provides enhanced maneuverability in confined environments as well as the capability to control the shape of the frame.

A second very unique aspect of the compliant framed mobile robot is its predisposition for modular mobile robotics. Reconfigurable modular robotic systems have been of keen interest to researchers during the last decade due to their improved ability to overcome obstacles and perform more tasks using a single hardware platform. Towards this goal, numerous researchers have devoted their efforts to investigating minimalist homogenous robotic modules that can be assembled in different formats to create sophisticated robotic systems that are more capable of adapting to uncertainty in their environment. These systems have examined reconfigurable manipulation [1], mobility [2-4], or a combination therein [5, 6]. Homogeneity of the modules is argued to reduce the number of spare parts required for maintenance, offer increased robustness through redundancy, provide compact and ordered storage, and increase the adaptability of the systems [7, 8]. The compliant frame allows this concept to be extended to wheeled mobile robots by allowing a number of different vehicle configurations to be formed from a set of uniform frame and axle modules.

The subject of this paper is the instrumentation of the flexible frame in order to obtain relative position and

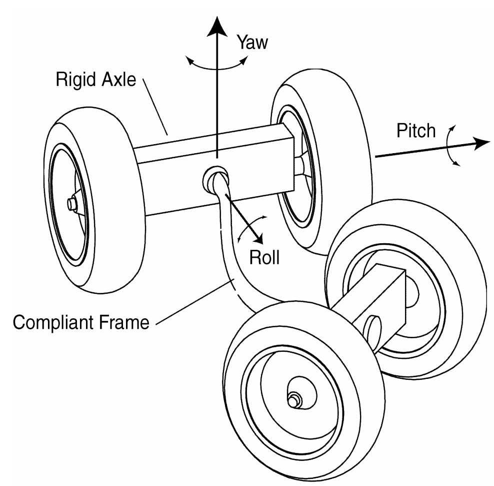

Figure 1. Compliant framed modular mobile robot.

orientation estimates of the axles. This data is critical for coordinating control and motion planning strategies for the robot [9], which inevitably requires information about the relative posture of each axle module. Traditional sensor data from each axle, such as wheel odometry and inertial measurements, may be accurate over short periods, but longer operation will result in drift of relative posture information. This will cause the controller to exert antagonistic internal forces and the motion planning algorithms will malfunction. In order to limit this drift, the frame module is instrumented with strain gages such that it can be used to sense the relative posture of the axles. This instrumentation and modeling of the frame module is the subject of this paper.

In order to fuse the internal frame data with traditional posture data, a Covariance Intersection Kalman Filter is proposed in Section 3. The derivation of the curvature model that is used to interpolate the relative posture of the axles, as well as the equations relating to the forces felt by the axle modules from the beam are given in Section 4. Experimental results comparing the predictions of relative posture and axial force from the curvature model are compared to the measured relative posture and axial load in section 5. A discussion of the results is provided in Section 6, and future work and concluding remarks are found in Section 7.

2. EXISTING ROBOTS

A limited number of compliant vehicles can be found in the literature, and none possess a similar highly compliant frame whose deflection is controlled by coordinated actuation of the wheels. Earliest found reference to compliant vehicles is a system proposed for planetary exploration that uses compliant members to provide roll and pitch degrees of freedom for suspension capability between the axles [10]. This concept was later extended [11] in a design where the frame of a vehicle was composed of at least one helical spring, but hydraulic cylinders were then to be used to control the deflection. In each of these cases, compliance was introduced for accommodating terrain. More recent research has introduced compliance for accommodating measurement error and resulting wheel slip occurring between independently controlled axle units on a service robot. This robot is similar in spirit to the compliant framed system in that it allows relative rotation between the axles, but this is provided by rotary joints connected to the ends of a frame with limited prismatic compliance [12]. The system is intended for operation on flat surfaces in industrial service settings. As the author states, the system provides high levels of mobility, but since the axle units are coupled by a relatively non conforming rigid frame, its ability to maneuver in confined environments will be limited [13]. In comparison to the system proposed here, the Borenstein system is likewise not intended for operating on uneven terrain, but in smoother and flatter manufacturing environments [12]. Other flexible robots use actuated articulated joints to provide similar relative motion between axles, as in the case of the Marsokhod rover [14] and other six wheeled research rovers with high relative DOF provided between axles modules [15]. The compliant frame mobile robotics system proposed here allows independent steering control of the axles with minimal slip and no additional hardware or actuators, as all of the above designs require. It does, however, present unique sensing challenges for localizing the relative position of the axles that the aforementioned robots with fixed joint structures do not experience.

3. SENSOR FUSION

Numerous examples can be found in the literature that use a Kalman type filter to fuse mobile robotics data. The typical approach is to use incremental encoder readings as the input to the mobile robot kinematic equations. This odometry model is then fused with another independent sensor, such as a gyroscope, inertial sensors, GPS, vision systems, some type of reflective sensor (laser, sonar, ir), or some combination of the above. The goal is to limit the impact of non-systematic odometry errors [12] and achieve the best possible posture evaluation with a method that eliminates or at least mitigates the drift inherent to the sensors commonly used on mobile robots.

In the algorithm proposed here, each axle module has the potential to fuse data from wheel encoders, rate sensors, accelerometers, and GPS using a kinematic model based Kalman filter as in [16]. In our case, the axle modules are initially assumed to be operating with two optical encoders, one for each wheel, and the flexible frame module will be instrumented with strain gauges. The frame module will create a sensor out of an internal structural component of the robot. While the literature is replete with examples of the fusion of more conventional sensors, very little is mentioned about the fusion of an instrumented compliant linkage with the standard odometry readings.

The closest example to our instrumented frame module is that described by Piedbeouf [17] for the purpose of predicting the endpoint position of a flexible linkage. While the curvature-based sensor model found there is similar to that presented in this paper, the fundamental constraints on the sensor as well as the beam itself are different. Peidbeouf requires only endpoint position relative to the root of the linkage for small deflections. The compliant framed mobile robot is more demanding in that it requires the sensor to return force, moment, and posture estimates in a system that will regularly exceed the common small deflection assumptions.

The closest found example to our research in mobile robotics is Borenstein's OMNImate [12] where the IPEC (Internal Position Error Correction) algorithm is proposed. This seems to be quite good at limiting the effect of odometry errors, but, no attempt is made to maintain variance information about each axles' posture. Variance information can be vital to a path-planning algorithm in deciding whether the robot posture is known with sufficient accuracy to permit close quarters maneuvering around objects. For this we will attempt to use a Kalman filter type approach that combines the error correction abilities of the IPEC algorithm with the variance maintaining attributes of the Kalman filter.

Bringing the beam sensor into the data fusion equation is complicated by the fact that the beam sensor has no new information in terms of the global coordinate frame; it is merely an observation of the relative pose (x, y, theta) of the two axles. As such, if the beam data is fused with the axle data in such a way as to decrease the variance of the axle pose, as in a traditional Kalman filter, then such an estimate is non-conservative. In other words it purports to improve the estimate of the axle posture – because it decreases the variance associated with it – but, in fact, it cannot do this because the beam merely observes the relative position and orientation of the two axles and knows nothing about the absolute posture of either axle.

The solution to this difficulty can be found in the covariance intersection filter strategy. This filter assumes 100% correlation between information sources in its fusion strategy and therefore does not produce non-conservative estimates in the face of correlated data [18]. The Covariance Intersection (CI) algorithm is stated as,

$$\begin{aligned} C &= \left(\omega A^{-1} + (1-\omega) B^{-1}\right)^{-1} \\ c &= C\left(\omega A^{-1} a + (1-\omega) B^{-1} b\right) \end{aligned} \qquad (1)$$

where {a, A} and {b, B} represent the {mean, variance} associated with datasets, and {c, C} likewise represents the fusion of {a, A} and {b, B}. The weighting factor, ω, is a parameter that determines which data set is trusted more. Thus the CI filter provides us with the ability to use the frame module to reduce odometry error and maintain conservative covariance estimates.

4. THE FLEXIBLE FRAME MODULE AS A SENSOR

It is desired to instrument the frame module in such a fashion that the relative position and orientation of each axle module can be detected by independent sensor data from the flexible frame. Such information is critical for dynamic stabilization of the robot and for implementing motion planning algorithms. It will also be helpful if the beam sensors relate information about the forces and moments applied by the beam on the axles. In order to obtain this information it is necessary to derive the Euler-Bernoulli beam equations for this system. Once a basic foundation is laid it is shown how a polynomial interpolation of the curvature of the beam can be obtained from the strain gauges as in [17]. With the curvature based model in hand the needed posture and force/moment information can be estimated.

A. Beam Model

Using the free body diagram shown in Figure 2, the following static equations of equilibrium can be determined,

$$\sum F_x = F_{xA} - F_{xB} = 0, \Rightarrow F_{xA} = F_{xB} = F_x \qquad (2)$$

$$\sum F_y = F_{yA} - F_{yB} = 0, \Rightarrow F_{yA} = F_{yB} = Fx \qquad (3)$$

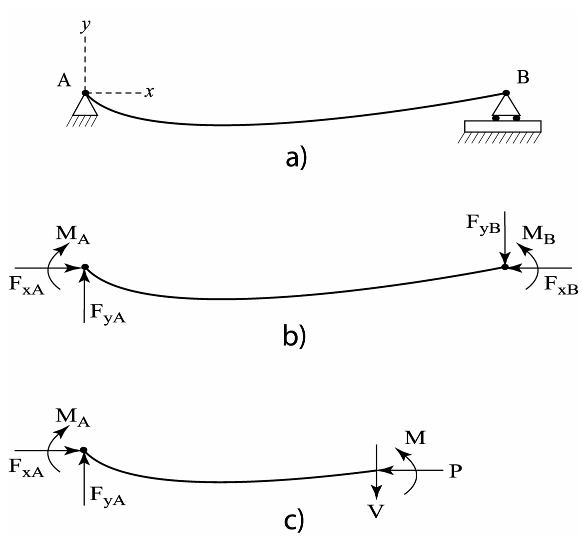

Figure 2 beam derivation diagrams

$$\sum M_A = -M_A + M_B - FyL = 0 \tag{4}$$

from which it can be shown that the y component of the boundary condition force is,

$$F_y = \frac{\left(-M_A + M_B\right)}{L} \tag{5}$$

Making a cut in the frame and drawing a new free body diagram, as in Figure 2c, we can make the following relationships about the forces and moments internal to the frame.

$$\sum F_x = F_{xA} - P = 0, \Rightarrow P = F_x \tag{6}$$

$$\sum F_y = F_y - V = 0, \Rightarrow V = F_y \tag{7}$$

$$\sum M_A = -M_A + M - Vx - P\upsilon = 0 \tag{8}$$

solving for M and plugging in the relationships from equations (6) and (7) yields,

$$M(x) = M_A + F_y x + F_x \upsilon(x) \tag{9}$$

From this it follows that the x component of the boundary condition force is determined by,

$$F(x) = \frac{M(x) - M_A - F_y x}{\upsilon(x)} \tag{10}$$

Once *M(x) and* $\upsilon(x)$ is provided by an interpolation of the sensor data, it is a simply matter to apply equations 5 and 10 to calculate the endpoint forces. Hence, a unique contribution of the frame sensor is that it specifically returns endpoint forces and moment estimates.

B. Sensor Instrumentation

The moments can be extrapolated from the strain gauge readings using the relationship below that relates all of the available strain data,

$$M(x) = \frac{\varepsilon(x) IE}{y} \tag{11}$$

where y is the distance from the point of inflection of the internal beam strain and the upper surface of the beam (nominally half of the beam thickness), and $\varepsilon(x)$ is a polynomial estimating the strain along the beam,

$$\varepsilon(x) = a_0 + a_1 x + a_2 x^2 \tag{12}$$

The resulting second order polynomial used here is one degree less than the number of strain gauge locations along the beam. Piedbeouf shows experimentally for his system that such a polynomial is an adequate representation for limited beam deflections [17].

The approximation *M(x)* can then be used to find the curvature, $\rho(x)$, along the beam,.

$$\frac{1}{\rho(x)} = \frac{M(x)}{EI} \tag{13}$$

Once $\rho(x)$ is known, path-wise integration of equation (14) then provides position and orientation of endpoint B relative to endpoint A.

$$\begin{aligned} d\theta &= \frac{dL}{\rho} \\ dx &= \rho \sin(\theta) \\ dy &= \rho(1 - \cos(\theta)) \end{aligned} \tag{14}$$

This procedure is illustrated in Figure 3.

It should be noted that the dynamic controller will be constantly trying to drive F_x to zero and at the same time the motion controller [9] will attempt to maintain a pure bending shape where $M_A = M_B$. Under this condition the curvature of the beam is constant for all x. Given a constant curvature, the pathwise integration of equation (14) will yield an accurate result even for a single step, dL, the size of the entire length of the beam. It should be noted that this result is valid even for large deflections.

We can then extract the deflection data at each strain gage location by using carefully chosen lengths, dL. Using this

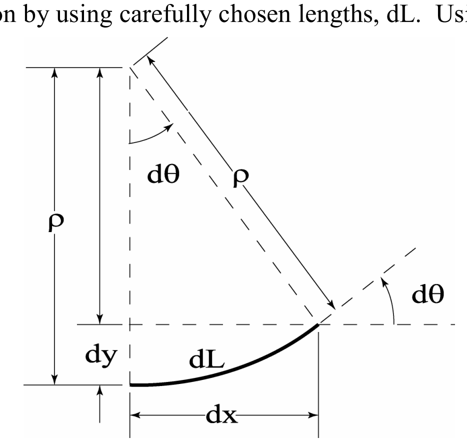

Figure 3. Beam curvature model.

data in equation (10), we can then predict, F_x.

5. EXPERIMENTAL RESULTS

In these experiments, a test stand similar in dimension to the frame module was constructed. It consisted of a pinned connection at each end of the beam, with a linear bearing at one end to allow changes in separation distance between the pivots. The angular and prismatic deflection of the endpoints was instrumented via a 12bit data acquisition system and highly linear potentiometers. The

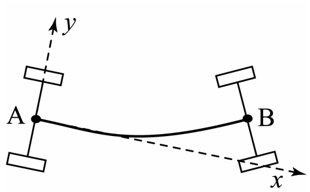

Figure 4. The position of B in the coordinate frame of A.

flexible portion of the beam itself was 0.3464m in length with strain gauges mounted at (0.0090, 0.1736, 0.3380)m along the beam. At each end, the beam was cantilevered to the pivots to emulate the actual axles of the robot. It was also possible to provide a longitudinal load to the beam in order to emulate the situation of non zero F_x.

The endpoints of the beam were then deflected -22.5°, -11°, 0°, 11°, and 22.5°. At each of these deflections, longitudinal loads of 0N, 1.0N, 2.0N, and 3.9N were applied to determine the affects of F_x. The resulting calculations of the relative x, y, and ϕ describe the point B in the rotated coordinate frame of A as shown in Figure 4. The results for x, y, and ϕ are shown in Figures 5 – 7 respectively. Predicted force data is shown in Figure 8.

6. DISCUSSION

Unfortunately the experimental fixture on which the

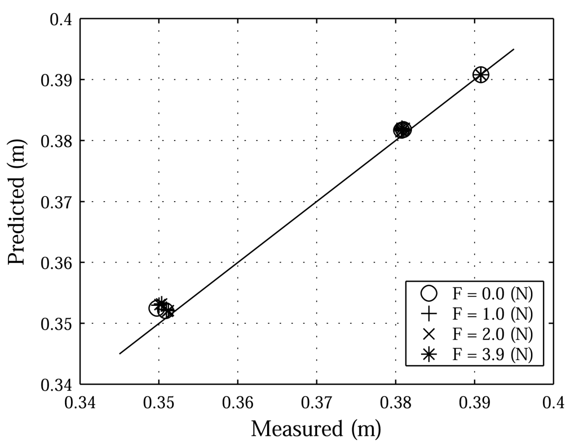

Figure 5. x – position of B relative to A.

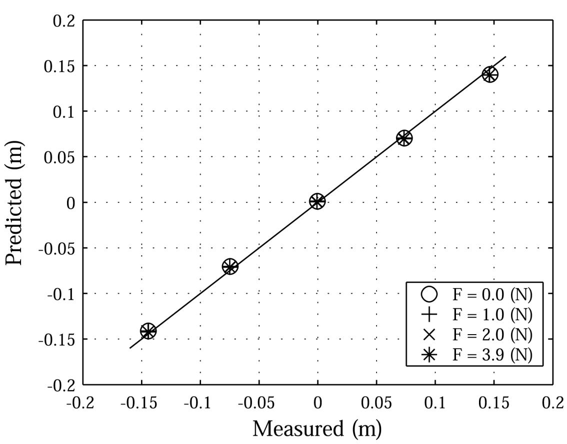

Figure 6. y – position of B relative to A.

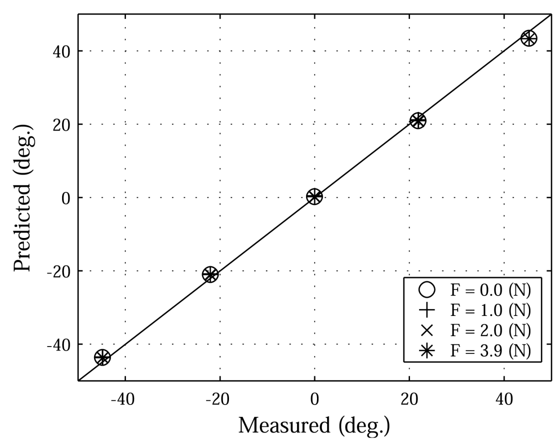

Figure 7. ϕ – orientation of B relative to A.

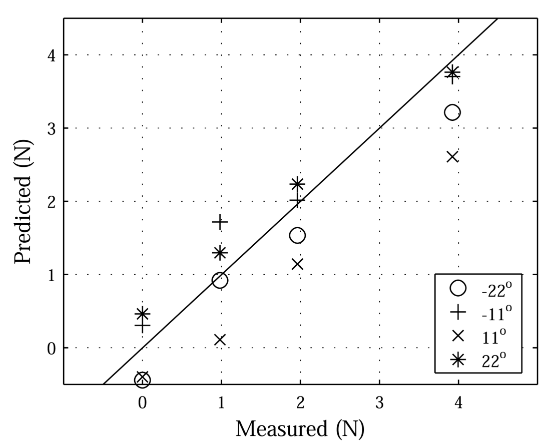

Figure 8. Longitudinal force.

instrumented beam was tested has appreciable friction in the prismatic motion that makes it difficult to apply an exact load to the test setup. An attempt was made to decrease the effect of this frictional force by taking a reading after releasing the fixture from tension and averaging it with a reading of the fixture released from compression. Future tests should focus on measuring the longitudinal force more accurately. Using linear regression, the correlation coefficient for the data in Figures 5 – 7 is greater than 0.999.

7. CONCLUSION

A sensor fusion strategy for compliant framed modular mobile robots based upon traditional Kalman Filters and Covariant Intersection filters are presented. Key to the later is the modeling and instrumentation of the frame module as an internal sensor for determining relative axle module posture. Experimental results have been presented which indicate that the model can perform well even under large deflections. Furthermore, the sensor model yields force data that can be used by the dynamic and motion controllers to correct errors.

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