

Mobile Manipulation Calibration

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1 Introduction

The frames of interest are listed in Table 1.

Table 1: Coordinate frames.

Name	Subscript
World	w
Mobile base	b
Base of arm	a
End effector	e
Tool	t

The pose \mathbf{T}_{wt} of an arbitrary tool attached to the end effector can be computed using the sequence of transforms

$$\mathbf{T}_{wt} = \mathbf{T}_{wb}(\mathbf{q}_b)\mathbf{T}_{ba}\mathbf{T}_{ae}(\mathbf{q}_a)\mathbf{T}_{et}, \quad (1)$$

where \mathbf{T}_{wb} depends on the base configuration $\mathbf{q}_b = [x_b, y_b, \theta_b]^T$ and \mathbf{T}_{ae} depends on the arm configuration \mathbf{q}_a .

2 Vicon Zero Pose

The `vicon_bridge` package allows one to provide a *zero pose* to specify the desired origin of a given model. Given the true robot frame $\{r\}$ and the Vicon model frame $\{v\}$, we have

$$\mathbf{T}_{wr} = \mathbf{T}_{wv}\mathbf{T}_{vr},$$

where \mathbf{T}_{vr} is a constant transform we need to calibrate. The zero pose \mathbf{T}_{wv}^0 is such that $\mathbf{T}_{wr} = \mathbf{I}$, which implies $\mathbf{T}_{wv}^0\mathbf{T}_{vr} = \mathbf{I}$ and thus

$$\mathbf{T}_{wv}^0 = \mathbf{T}_{vr}^{-1} = \begin{bmatrix} \mathbf{C}_{rv} & \mathbf{r}_r^{vr} \\ \mathbf{0}^T & 1 \end{bmatrix}$$

2.1 Vicon Object Origin

The origin can be manually placed at a desired location by physically placing a marker at this location, setting it to be zero (or another desired offset from the origin) in the Vicon software, and then removing the marker from the object model.

3 Base Calibration

3.1 Center of Rotation

We need to calibrate the Vicon measured base poses $\hat{\mathbf{T}}_{wv}$ so that the origin of \mathbf{T}_{wb} is correct (i.e., we want it at the center of rotation, such that there is no translational motion when the base is commanded to rotate). Starting at an arbitrary configuration $\hat{\mathbf{T}}_{wv,0}$, we will move the base to a sequence of desired yaw angles θ_i^d and obtain the corresponding measured configurations $\hat{\mathbf{T}}_{wv,i}$. We want to find \mathbf{r}_v^{bv} such that $\hat{\mathbf{r}}_{wb,i} = \hat{\mathbf{r}}_{wb,0}$ is satisfied as closely as possible for each i , which yields the least-squares problem

$$\operatorname{argmin}_{\mathbf{r}_v^{bv}} \frac{1}{2} \sum_i \left\| \hat{\mathbf{C}}_{wv,i} \mathbf{r}_v^{bv} + \hat{\mathbf{r}}_{w,i}^{vw} - \hat{\mathbf{C}}_{wv,0} \hat{\mathbf{r}}_v^{bv} - \hat{\mathbf{r}}_{w,0}^{vw} \right\|^2. \quad (2)$$

This gives us \mathbf{r}_v^{bv} , but what we want for the Vicon zero pose is $\mathbf{r}_b^{vb} = -\mathbf{C}_{bv} \mathbf{r}_v^{bv}$, so we need to negate the value and be careful to rotate it from the Vicon frame to the base frame if $\mathbf{C}_{bv} \neq \mathbf{I}$.

We can write (2) in the form $\|\mathbf{A}\mathbf{x} - \mathbf{b}\|^2$ by taking $\mathbf{x} = \mathbf{r}_v^{bv}$ and

$$\mathbf{A} = \begin{bmatrix} \hat{\mathbf{C}}_{wv,0} - \hat{\mathbf{C}}_{wv,0} \\ \vdots \\ \hat{\mathbf{C}}_{wv,n} - \hat{\mathbf{C}}_{wv,0} \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} \hat{\mathbf{r}}_{w,0}^{vw} - \hat{\mathbf{r}}_{w,0}^{vw} \\ \vdots \\ \hat{\mathbf{r}}_{w,0}^{vw} - \hat{\mathbf{r}}_{w,n}^{vw} \end{bmatrix}.$$

3.2 Orientation (Yaw)

We also need to calibrate the Vicon measured base poses $\hat{\mathbf{T}}_{wv}$ so that the yaw angle of the model is aligned with the actual forward direction of \mathbf{T}_{wb} ; that is, the direction of pure forward velocity. Starting at a particular pose $\hat{\mathbf{T}}_{wv,0}$, we command the Ridgeback to drive forward and periodically measure the pose $\hat{\mathbf{T}}_{wv,i}$. Ideally, the position of the base would be aligned with the x -axis of the initial frame. Let $\mathbf{p}_i = \mathbf{C}_{wv,0}^T (\mathbf{r}_{w,i}^{vw} - \mathbf{r}_{w,0}^{vw})$. The yaw error is $\Delta\theta_i = \arctan2(p_{y,i}, p_{x,i})$. We then solve the problem

$$\operatorname{argmin}_{\theta_{vb}} \frac{1}{2} \sum_i (\theta_{vb} - \Delta\theta_i)^2, \quad (3)$$

with corresponding Vicon zero orientation $\mathbf{C}_{bv} = \mathbf{C}_z(-\theta_{vb})$.

Important: remember to take this into account when computing the overall base zero pose including the position, as discussed above.

We can write (3) in the form $\|\mathbf{A}x - \mathbf{b}\|^2$ by taking $x = \theta_{bv}$, \mathbf{A} a vector of ones, and \mathbf{b} a vector of the angle errors $\Delta\theta_i$.

4 Arm-End Effector-Tool Calibration

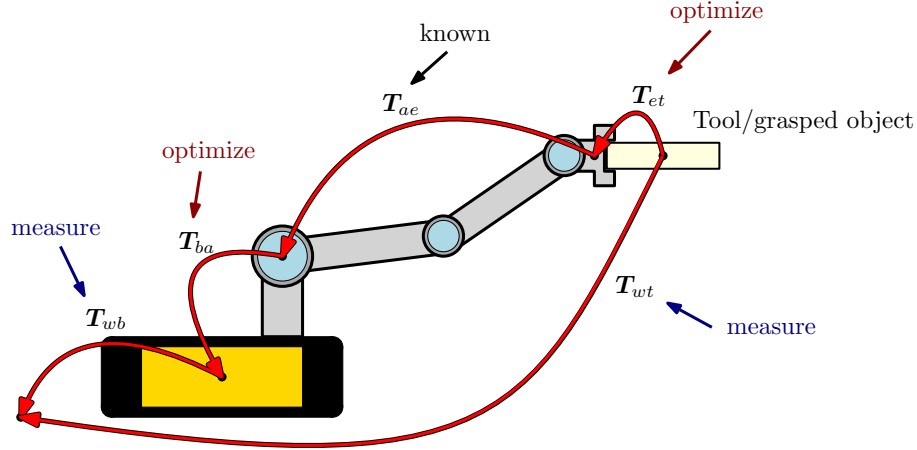


Figure 1: Frames on the robot being calibrated.

Having calibrated the base pose T_{wb} , we now wish to calibrate (static) the transforms between the base and arm T_{ba} and the EE and tool T_{et} . We will assume that factory calibration for the arm transform $T_{ae}(\mathbf{q}_a)$ is good enough.

To do so, we will collect a sequence of pairs $(\mathbf{q}_{a,i}, \hat{T}_{wt,i})$ by moving the arm to the sequence of configurations $\mathbf{q}_{a,i}$. We will then solve the (nonlinear) least squares problem

$$\operatorname{argmin}_{T_{ba}, T_{wt}} \frac{1}{2} \sum_i \|\Xi(T_{wt}(\mathbf{q}), \hat{T}_{wt,i})\|^2. \quad (4)$$

over the manifold $SE(3)$, where T_{wt} is computed using (1) and

$$\Xi(T_1, T_2) = \log(T_1^{-1}T_2)^\vee \quad (5)$$

is the error between the poses. We can include any prior information about the transforms as an initial guess for the solver.

5 Force Sensor Calibration

Here our goal is to find the orientation \mathbf{C}_{bf} of the force sensor frame $\{f\}$ about the x - and y -axes of a frame $\{b\}$ with a gravity-aligned z -axis. To do so, we

will zero the sensor and then attach a mass m to it and collect a set of force measurements $\{\mathbf{f}_{f,i}\}_{i=1}^n$. We then solve the nonlinear least-squares problem

$$\underset{\Delta \mathbf{C} \in SO(3)}{\operatorname{argmin}} \frac{1}{2} \sum_i \|\Delta \mathbf{C} \bar{\mathbf{C}}_{bf} \mathbf{f}_{f,i} - m \mathbf{g}\|^2$$

for the orientation offset $\Delta \mathbf{C}$ such that $\mathbf{C}_{bf} = \Delta \mathbf{C} \bar{\mathbf{C}}_{bf}$ with $\bar{\mathbf{C}}_{bf}$ a nominal guess for the orientation.

Calibrating the yaw angle offset would be more complicated, and at least require multiple orientations of \mathbf{C}_{bf} to identify.