Robotic Valve Turning: Axial Misalignment Estimation from Reaction Torques

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Aim

To predict reaction torques as a function of axis misalignment during rotation of the valve.

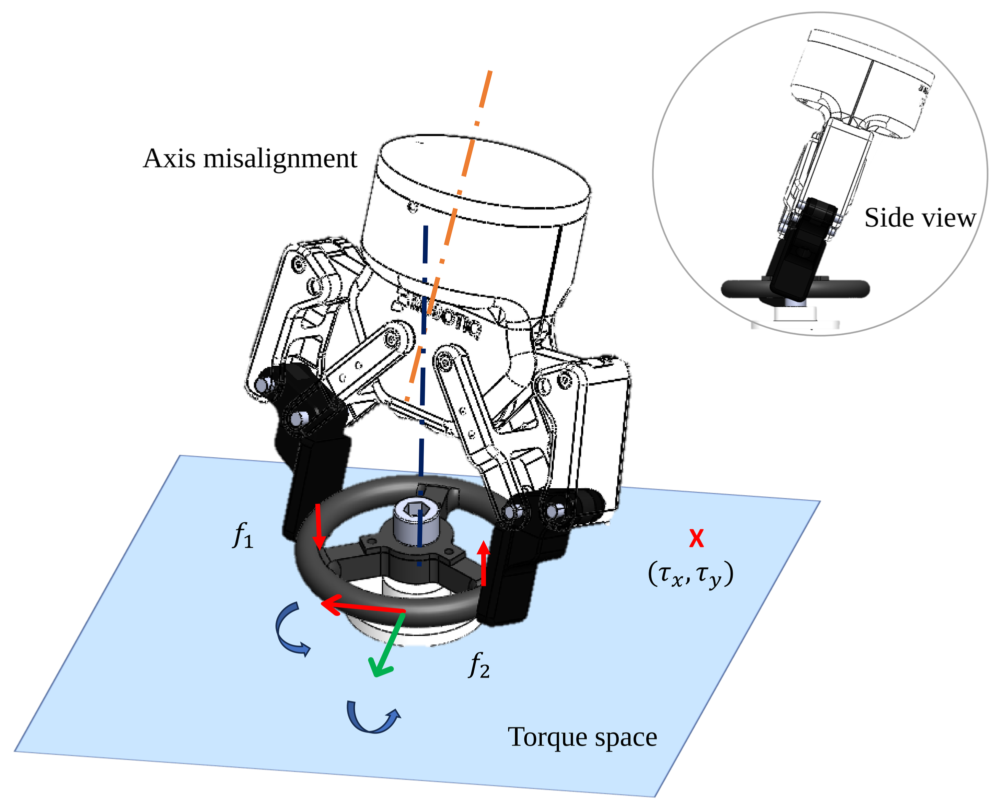
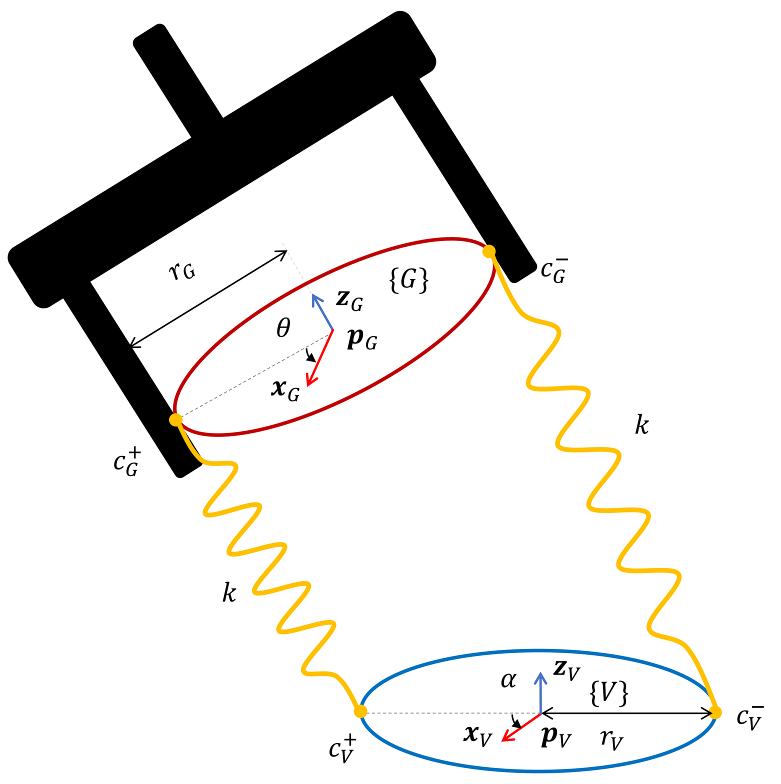


Fig. 1: Valve turning using parallel jaw gripper with axis misalignment.

Quasi-static Misalignment Model



Variables	Symbols
Frame associated with the gripper	$\{G\}$
Frame associated with the valve	$\{V\}$
Gripper contact parameter (controlled variable)	θ
Valve contact parameter (uncontrolled variable)	α
Radius w.r.t gripper	r_G
Radius w.r.t valve	r_V
Misalignment errors	n_1, n_2
Grasping points on the gripper	c_G^+, c_G^-
Grasping points on the valve	c_V^+, c_V^-
Stiffness of the surface material on the gripper	k
Energy potential	E
Forces	f_G, f_V
Torques	τ_G, τ_V

Fig. 2: Axial misalignment denoted by the relative orientation of $\boldsymbol{z}_G$ and $\boldsymbol{z}_V$.

Assuming a small non-zero misalignment between the z-axis of the valve and the gripper axis, the contact points on the gripper are defined as:

$$\boldsymbol{c}_G^+(\theta) = r_G(\cos(\theta)\boldsymbol{x}_G + \sin(\theta)\,\boldsymbol{y}_G + \boldsymbol{p}_G$$
$$\boldsymbol{c}_G^-(\theta) = \boldsymbol{c}_G^+(\theta + \pi)$$

Similarly for the valve,

$$\boldsymbol{c}_V^+(\alpha) = r_V(\cos(\alpha)\boldsymbol{x}_V + \sin(\alpha)\,\boldsymbol{y}_V + \boldsymbol{p}_V$$
$$\boldsymbol{c}_V^-(\alpha) = \boldsymbol{c}_V^+(\alpha + \pi)$$

Modeling the interaction between the gripper and valve as elastic deformation of springs between the contact points; the elastic potential energy is:

$$E(\alpha,\theta) = \frac{1}{2}k||\,\boldsymbol{c}_G^+(\theta) - \boldsymbol{c}_V^+(\alpha)||^2 + \frac{1}{2}k||\,\boldsymbol{c}_G^-(\theta) - \boldsymbol{c}_V^-(\alpha)||^2$$

The quasi-static contact condition, $\nabla_\theta \mathrm{E} = 0$. Solving this equilibrium condition for θ^*:

$$\theta^*(\alpha) = arctan2(-n_1 n_2 + \sqrt{n_1^2 + n_2^2 + 1}\,tan(\alpha), n_2^2 + 1$$

Force acting on the two points are:

$$\boldsymbol{f}^+ = k(\boldsymbol{c}_V^+(\alpha) - \boldsymbol{c}_G^+(\theta))$$
$$\boldsymbol{f}^- = k(\boldsymbol{c}_V^-(\alpha) - \boldsymbol{c}_G^+(\theta))$$

Torque can then be written as:

$$\boldsymbol{\tau}_V(\alpha,\theta,n_1,n_2) = \boldsymbol{c}_V^+ \times \boldsymbol{f}^+ + \boldsymbol{c}_V^- \times \boldsymbol{f}^-$$

Expected Torque Space Results

Geometric Features:

1. A single torque space ellipse is produced for half rotation of the valve.
2. Length of the vector (n_1, n_2) is proportional to the size of the torque ellipse.
3. The vector is always tangent to the ellipse.

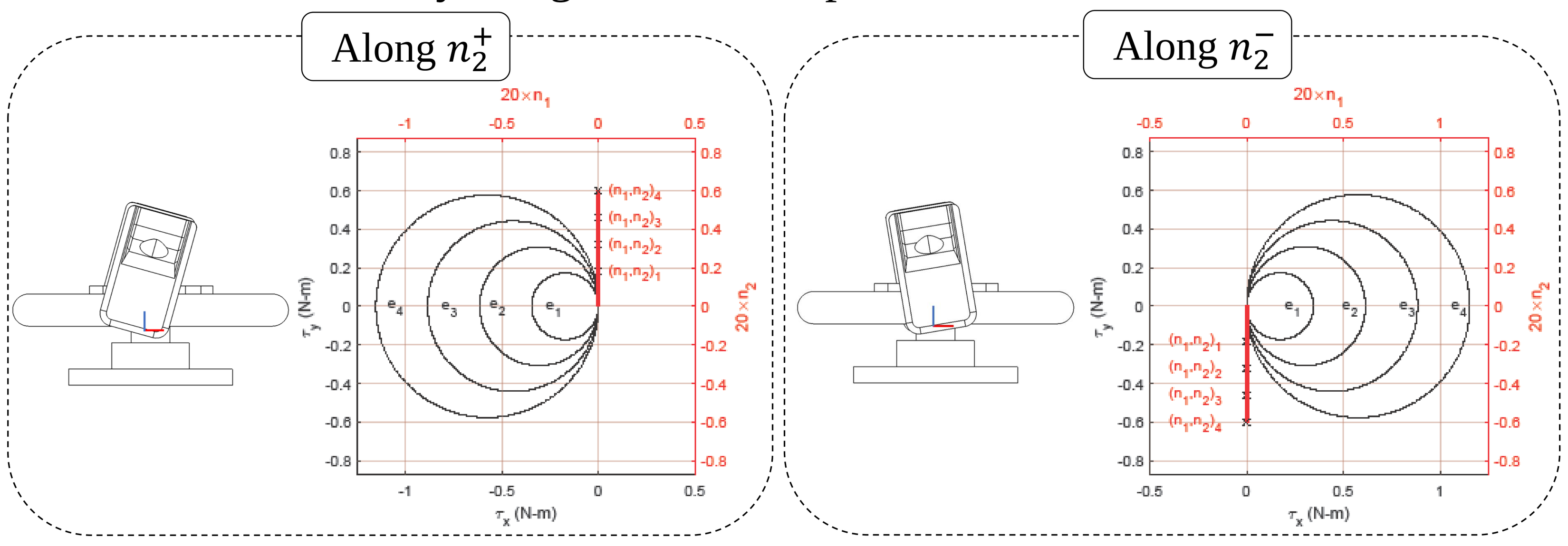


Fig. 3: Gripper configuration being varied along n_2 - denoted by n_2^+ and by n_2^- resulting in expected torque space ellipses (in simulation) along x-axis with $n_1 = 0$.

Experimental Validation

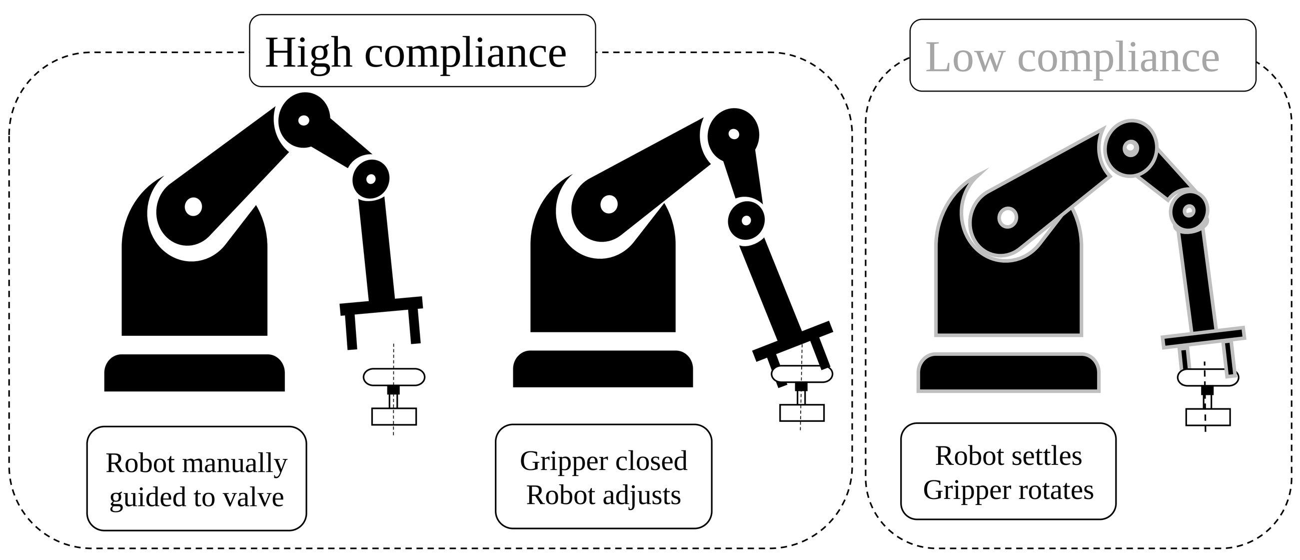


Fig. 4: Protocol: High compliance mode allows robot to adjust to reaction forces/torques.

Analyzing the Valve Torques

Estimating the gripper axis misalignment by satisfying the unitary condition:

$$\frac{\tilde{n}_1}{\tilde{n}_2} = \frac{z_{G,x}}{z_{G,y}}$$

$$\sqrt{z_{G,x}^2 + z_{G,x}^2 + z_{G,x}^2} = 1$$

$$\tilde{n}_1(t) = \mathrm{sgn}(z_{G,z}(t))\frac{z_{G,x}(t)}{z_{G,z}(t)}$$

$$\tilde{n}_2(t) = \mathrm{sgn}(z_{G,z}(t))\frac{z_{G,y}(t)}{z_{G,z}(t)}$$

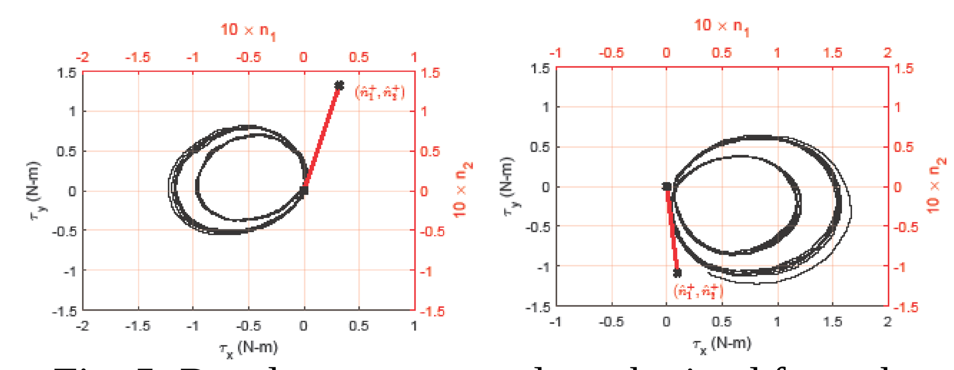


Fig. 5: Resultant $\tau x - \tau y$ plots obtained from the experiments with $(\hat{n}_1, \hat{n}_2)$ tangent to the torque-ellipses.

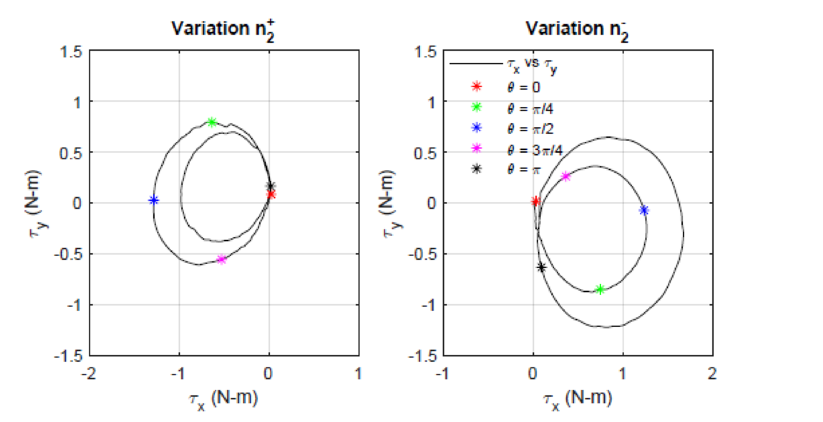


Fig. 6: Gripper parameter with initial condition θ_0 from experimental data highlighting the key checkpoints when $\theta = [0, \pi/4, \pi/2, 3\pi/4, \pi] + \theta_0$.

Conclusion

There is a geometric relation between the reaction torques and axis misalignment. Specifically, the misalignment vector is tangent to the reaction torques and its length is proportional to the magnitude of the reaction torques. Also, the frequency of torques is twice the frequency of valve rotation.

Modeling Reaction Forces to Estimate Misalignment During Valve Rotation

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