공학석사 학위논문

작업용 거대 비행 스켈레톤 시스템을 위한 분산 IMU 사용 접촉력 추정 기법 개발

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2021 년 8 월

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Abstract

Contact Wrench Estimation for Large-Size Operational Aerial Skeleton System with Distributed IMUs

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In this paper, we propose the novel external wrench estimator for large-size aerial skeleton system with distributed rotor action (LASDRA) which exploits multiple distributed IMUs. The proposed wrench estimator reduces the delay of a conventional momentum-base observer, which using only velocity information, by fuse the acceleration information from distributed IMUs with Kalman Filter. Also, angular acceleration estimation utilizes multiple IMU signals are proposed to improve external torque estimation accuracy. The delay reduction of the proposed wrench estimator was verified in simulation and also experiment verification at 3-link LASDRA is proceed.

Keywords: Sensor fusion, Wrench estimation, Unscented Kalman filter, Aerial manipulation
Student Number: *2019-20151*

Contents

List of Figures

List of Tables

Abbreviations

Large-size **A**erial **S**keleton with **D**istributed **R**otor **A**ctuation

Omni-**D**irectional **A**erial **R**obot

Force-**T**orque sensor

Momentum-**B**ased **O**bserver

Inertial **M**easurement **U**nits

Unscented **K**alman **F**ilter

Extended **K**alman **F**ilter

High **O**rder **D**isturbance **O**bserver

Unscented **T**ransform

Chapter 1

Introduction

1.1 Motivation

To expand the physical manipulation capabilities of humans into the air, research about aerial manipulation with multi-rotor drone and manipulator systems [1] - [2] or omni-directional drones [3]-[4] were introduced. However, multi-rotor drone and manipulator systems and omni-directional drones have limitations with aerial manipulation. They have limited operation time (10-15 minutes) and an insufficient payload due to the limited capacity of the battery. Also, the difficulty of accurate onboard sensing and control can cause falls and collisions with the environment.

Figure 1.1: Downsized LASDRA with joint locking device.

To overcome the limitations of these aerial manipulation platforms, Large-size Aerial Skeleton with Distributed Rotor Actuation (LASDRA) [5] was proposed, which is composed of multiple links of Omni-Directional Aerial Robot (ODAR) [6]. Precise pose estimation [5] with kinematic constraints on LASDRA and distributed impedance control that allows compliant operation was demonstrated. Also, a downsized LASDRA system with a novel joint locking device was developed, which increases the end-effector's payload by distributing the external load. With developed LASDRA, manipulation of lifting 1.2 kg weight was available as shown in Fig. 1.1.

To manipulate with LASDRA, accurate force-torque control is required. To control the force and torque, a contact wrench between the effector of LASDRA and the external environment should be measured. Although an external wrench can also be measured by mounting a force-torque sensor (FT sensor) at the end-effector of LASDRA, it is difficult to use in practice because FT sensor requires high cost and can only measure the wrench at the mounted position. And also if we use FT sensor at the end of LASDRA, a long connection wire (7 m) should be mounted to connect base and the FT sensor at the end. A thick wire will have to be used to transmit signals over a long distance, which will lead to a reduction in the payload of LASDRA. For these reasons, the contact wrench of LASDRA should be estimated using a wrench estimator that estimates external forces only from onboard sensor information.

The wrench estimator uses the acceleration or velocity information from the onboard sensors and with the dynamics to estimate the external wrench. There is two typical wrench estimator, momentum-based observer (MBO) [7] and inverse dynamics. MBO is an observer that converges to a constant wrench, by integrate velocity information recursively. Typical robotic arms obtain the acceleration of joints by differentiating joint angles measured from encoders. The acceleration information obtained by differentiating encoder information twice is too noisy to immediately substitute to inverse dynamics, so typical robotic arms use MBO which uses velocity information to estimate external wrench. MBO gives accurate and stable estimation when the external wrench changes slowly. But MBO gives delayed estimation when the external wrench changes rapidly because it is the form of the observer.

But in LASDRA, a better performance wrench estimator can be used by fusing MBO and inverse dynamics method, because LASDRA has an inertial measurement unit(IMU) at each link and provides both velocity and acceleration information unlike with previous robotic arms. By exploiting this characteristic, we propose a novel wrench estimator that fuses MBO and inverse dynamics with Unscented Kalman Filter(UKF) [8]. The proposed wrench estimator shows showed less delay than MBO and less noise than inverse dynamics.

1.2 Related Works

The wrench estimators that use velocity or acceleration information of robot, MBO and inverse dynamics, are introduced in [7]. And especially in multi-rotor drone, Lyapnov based nonlinear wrench observer was introduced, which is a similar form with MBO and use velocity and angular velocity information. These estimators have limitations in delay or noise. Inverse dynamics with acceleration show direct response, but also have a noisy response by inaccurate measurement of acceleration. MBO with velocity shows the less noisy response at constant external wrench, but shows delayed response when external wrench change rapidly because of its converge filter form.

Various researches are conducted to improve the performance of the wrench estimator. The first method is to fuse velocity and acceleration information with high order disturbance observer (HODO) which is introduced in [9]. HODO assumes external wrench is following high order random work dynamics, and regard external wrench as one of the state vector. States including external wrench corrected with velocity and acceleration measurements. In [10] and [11], HODO using Extended Kalman filter (EKF) form has applied in drone and drone-manipulator system. HODO shows more fast response and is less sensitive to noise than MBO in [10] and [11]. And in [12], UKF form HODO was applied to a drone, to improve convergence by more accurate approximation of nonlinearity. But these HODO methods cannot ensure convergence, because HODO is assuming external wrench as random walk dynamics and approximate nonlinear dynamics to linear.

The second method is to measure velocity and acceleration more accurately by attaching additional IMUs. In [13], accurate velocity and acceleration measurement by attaching additional IMU at the joint of the robotic arm. By fuse joint angle and IMU information with EKF, more accurate velocity and acceleration measurements were possible. As a follow-up to this, collision detection by MBO and inverse dynamics which use accurately measured velocity and acceleration in [14]. It detects collision immediately by using inverse dynamics with measured acceleration, but an estimated wrench is too noisy to use at control because the wrench is calculated algebraically without any filters.

1.3 Contribution

The contributions of this research are :

- The novel wrench estimator is proposed, which shows a faster and stable response than typical wrench estimators (MBO, inverse dynamics) by exploiting LASDRA's distributed and multiple IMUs.
- Force estimation performance has increased by use **acceleration** information with MBO.
- Torque estimation performance also increased by using angular acceleration information obtained by multiple IMUs signals.
- The proposed wrench estimator is verified in simulation and experiment.

Chapter 2

Preliminary

2.1 LASDRA System

2.1.1 System Description

LASDRA system [15] is an aerial manipulation platform that is composed of multiple links of ODAR [6]. Each link can generate arbitrary 6 degrees of freedom (DoF) wrench in any direction of posture as shown in Fig. 2.1, by using redundant 8 rotors. Each link is connected with a joint locking device as shown in Fig. 2.2, which can lock joints variably when manipulating. The joint locking device distributes the payload of the distal link among the other links to increase the payload of the end-effector [15].

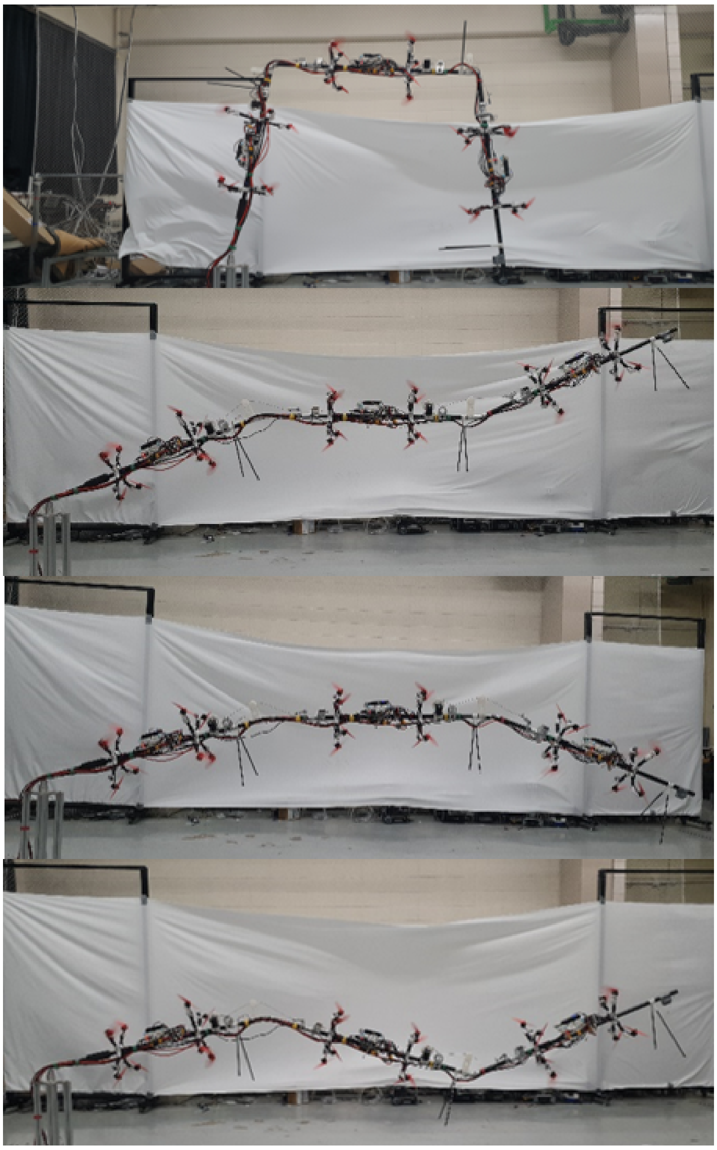

Figure 2.1: LASDRA flight in various configurations

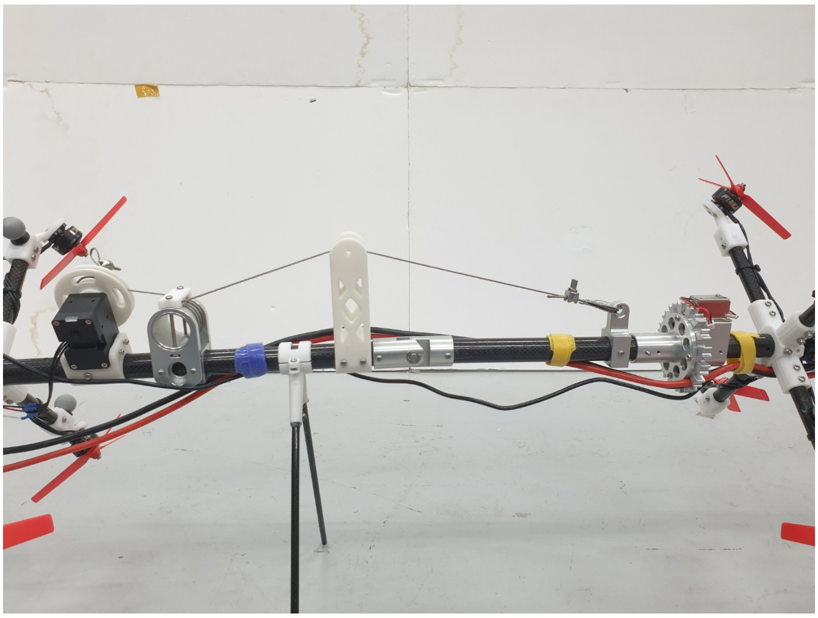

Figure 2.2: 2-DoF joint locking device based on capstan brake and latch

2.1.2 Estimation of LASDRA

Each link is controlled and estimated with Raspberry Pi 3[1] and Pixhawk 2.4.8[2]. Pixhawk has an embedded IMU (Inertial Measurement Unit) and barometer. Pixhawk estimates position, velocity, attitude, gyroscope bias, and accelerometer bias by fuse onboard sensor data (accelerometer and gyroscope of IMU) and external sensor data (GPS or MOCAP) with built-in EKF. Especially in outside, the pose of each link are corrected by exploiting kinematic constraints with SCKF (Smoothly Constrained Kalman Filter) [5].

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[1] https://www.raspberrypi.org/

[2] https://pixhawk.org

2.2 Wrench estimator

In this part, LASDRA dynamics and detailed formula of MBO and inverse dynamics will be described. Proposed wrench estimator fuse these estimators with UKF form.

2.2.1 Dynamics

The proposed wrench estimator distributedly estimates the external wrench of each link and adds a base to the end to finally estimate the external force acting on the end-effector. Therefore, for wrench estimation, we should use dynamics that are expressed in maximum coordinate for each link. Translation and rotational dynamics of each link are expressed in

$$\begin{aligned} ma &= RB_f u - mge_3 + f_e \\ J\alpha &= Jw \times w + B_\tau u - r_{cm} \times mge_3 + \tau_e \end{aligned} \tag{2.1}$$

First line of equation (2.1) is translation dynamics derived about space coordinate. m is mass of link, R $(= R_{SB}^{B})$ is rotation matrix of link, $u \in R^8$ is rotor thrust input vector, B_f is mapping matrix from input u to thrust force, and f_e is external force. Second line of equation (2.1) is rotational dynamics derived about body coordinate. J in momentum of inertia , w $(= w_b)$ is body angular velocity,

B_τ is mapping matrix form input u to thrust torque, τ_e is external torque, and r_{cm} $(= r_{cm}^B)$ is position vector from geographic center to center of mass.

2.2.2 Inverse dynamics

When accelerations a, α and angular velocity ω measured, external force and torque f_e, τ_e can be calculated algebraically as equation (2.2)

$$\begin{aligned} \hat{f}_e &= m\hat{a} - \hat{R}B_f u + mge_3 \\ \hat{\tau}_e &= J\hat{\alpha} - J\hat{\omega} \times \hat{\omega} - B_\tau u + r_{cm} \times mge_3 \end{aligned} \tag{2.2}$$

It is called inverse dynamics. Inverse dynamics can directly calculate external wrench but is hard to use in control because it is too much sensitive to the noise of a and α.

2.2.3 Momentum based observer

Momentum based observer is wrench observer that use velocity measurement v and ω. It converges estimated wrench $\hat{f}_e, \hat{\tau}_e$ to f_e, τ_e recursively by integrate recursively with translational and rotational momentum p_r, p_t. The observer equation of momentum based observer are

$$
\begin{aligned}
\dot{\hat{f}}_e &= K(\dot{p}_t - \dot{\hat{p}}_t) = K(ma - m\hat{a}) \\
\dot{\hat{\tau}}_e &= K(\dot{p}_r - \dot{\hat{p}}_r)
\end{aligned}
\tag{2.3}
$$

By integral each side of (2.3), we can get a complete observer equation of MBO as

$$
\begin{aligned}
\hat{f}_e &= K(m\hat{v}(t) - m\hat{v}(0) - \int_0^t \hat{f}_{in} + \hat{f}_e \ dt) \\
&= K(m\hat{v}(t) - \int_0^t \hat{R}B_f\hat{u} - mge_3 + \hat{f}_e \ dt) \\
\hat{\tau}_e &= K(J\hat{w}(t) - J\hat{w}(0) - \int_0^t J\hat{w} \times \hat{w} + \hat{\tau}_{in} + \hat{\tau}_e \ dt) \\
&= K(J\hat{w}(t) - \int_0^t J\hat{w} \times \hat{w} + B_\tau u - r_{cm} \times mge_3 + \hat{\tau}_e \ dt)
\end{aligned}
\tag{2.4}
$$

Error dynamics of momentum based of observer are shown as

$$
\begin{aligned}
\dot{e}_f &= Ke_f + \dot{f}_e \\
\dot{e}_\tau &= Ke_\tau + \dot{\tau}_e
\end{aligned}
\tag{2.5}
$$

As seen in the (2.5), when external wrench changes slowly ($\dot{f}_e, \dot{\tau}_e \approx 0$), MBO will estimate external wrench correctly. But, in a dynamic situation, an error will cause by delayed estimation. Our novel wrench estimator alleviates this limitation by fuse momentum base observer with inverse dynamics.

Chapter 3

Wrench estimator algorithm

In this chapter, the detailed algorithm of the proposed wrench estimator will be explained. The wrench estimator operates distributedly on each link. It measures the external wrench of each link and then accumulates external wrenches from the base to the end to obtain the wrench acting on the end. The wrench on the base is necessarily measured by FT sensor. The first section is about the wrench estimator algorithm at each link, and the second section is about accumulating estimation results of each link.

3.1 Wrench estimation of each link

3.1.1 Sensor measurements

To estimate the external wrench of each link of LASDRA, IMU in Pixhawk board, MOCAP, and additional accelerometers in Fig. 3.1 are used. Pixhawk IMU at the center of the mass of the link measures acceleration and angular velocity. Additional accelerometers attached 0.5 m far away from the center measure acceleration of the end of the link. MOCAP measures position and quaternion posture data. By filtering these sensor measurements with the following pipeline, an external wrench can be estimated.

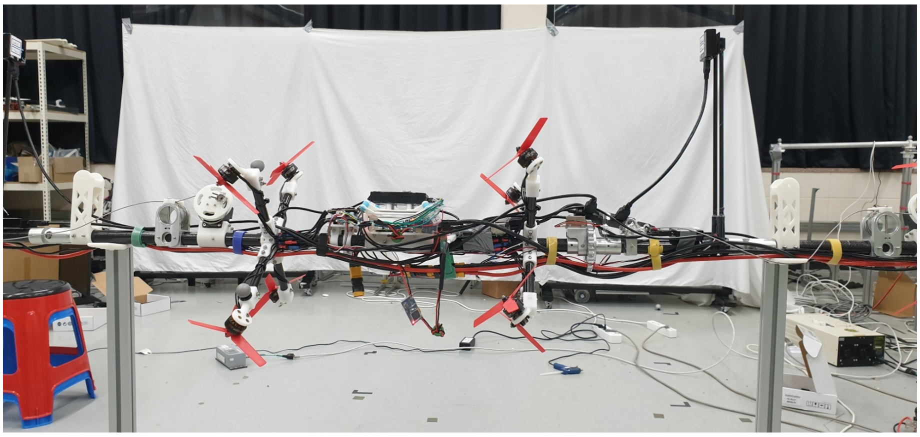

FIGURE 3.1: Sensors of LASDRA

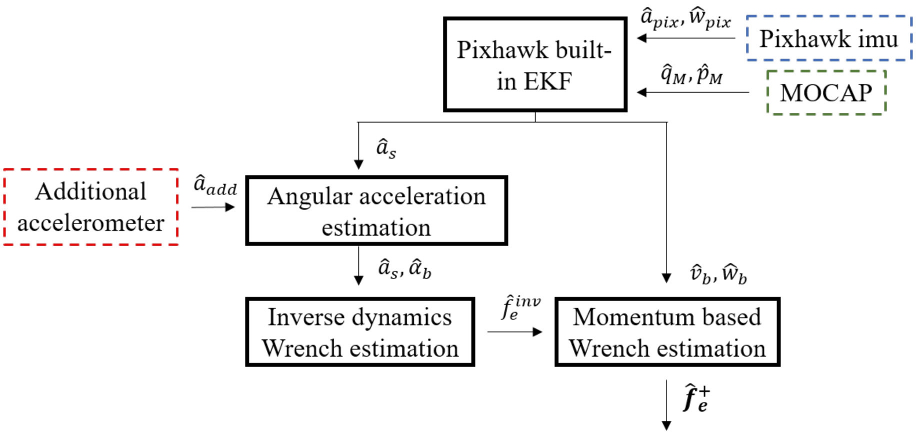

FIGURE 3.2: Pipeline of the wrench estimator at each link

3.1.2 Wrench estimator pipeline

The proposed wrench estimator has a pipeline of Fig. 3.2, at each link of LASDRA.

First, Pixhawk estimates position, velocity, posture, and accelerometer, and gyroscope bias. Pixhawk fuse IMU and MOCAP measurements with built-in EKF. Second, angular acceleration is estimated by the difference of an additional accelerometer at the end of the link and Pixhawk accelerometer at the center of the link. By get the difference of the acceleration, pure rotational acceleration is obtained. Lastly, the external Wrench is estimated by use velocity, angular velocity, acceleration, and angular acceleration information from the previous step. MBO propagates wrench information with velocities, and inverse dynamics correct propagated wrench information with accelerations. The correction with a directly measured wrench with acceleration makes more accurate wrench estimation to be possible. Detailed equations of each step are explained in the following sections.

3.1.3 Pixhawk built-in EKF

Pixhawk flight controller uses IMU and MOCAP to estimate the state of the drone with EKF. Built-in EKF of Pixhawk tracks position, velocity, orientation, accelerometer bias, and gyroscope bias [16]. It uses accelerometer and gyroscope measurement to the propagation of state and correction with MOCAP. So from the built-in EKF, position, orientation, velocity, angular velocity, acceleration are obtained.

3.1.4 Angular acceleration estimation

To estimate external torque, angular acceleration should be measured. Differentiate angular velocity shows very noisy results and is impossible to use at torque estimation. So we attach additional IMUs at the end of the link and get a difference of acceleration between the center and the end of the link. i^{th} additional accelerator gives acceleration measurement a_i as

$$a_i = R_{b,i}^T [a_b + \alpha_b \times r_{b,i} + w_b \times (w_b \times r_{b,i}) + n_i] \tag{3.1}$$

$R_{b,i}$ and $r_{b,i}$ are rotation matrix and position vector between link body to an accelerometer. a_b, α_b, and w_b are body acceleration, angular acceleration, a nd angular velocity of link. n_i is accelerometer noise. a_b and w_b are expressed by subtract sensor bias from the gyroscope and accelerometer measurements as (3.2), which estimated with built-in EKF of Pixhawk.

$$\begin{aligned} a_b &= a_{pix} - a_{bias,pix} + n_a \\ w_b &= w_{pix} - w_{bias,pix} + n_w \end{aligned} \tag{3.2}$$

n_a and n_w are sensor noise of Pixhawk accelerometer and gyroscope. By subtract (3.2) to (3.1), simple measurement equation about α_b is expressed as

$$\begin{aligned} R_{b,i}a_i - a_b - w_b \times (w_b \times r_{b,i}) \\ = y_i = -[r_{b,i}]_\times \alpha_b + N_i \end{aligned} \tag{3.3}$$

N_i is fused noise, which contains n_a and uncertainty of $w_b \times r_{b,i}$. Uncertainty of $w_b \times r_{b,i}$ obtained by Unscented Transform(UT). Also numerical differential of w_b gives equation about α_b as

$$w_b(t) - w_b(t-1) = \alpha_b(t) + n_w + n_w \tag{3.4}$$

By stack (3.3) and (3.4), final estimation equation about α_b is written as

$$Y = \begin{bmatrix} y_1 \\ \cdots \\ y_n \\ w_b(t) - w_b(t-1) \end{bmatrix} = H\alpha_b + N = \begin{bmatrix} [r_{b,1}]_\times \\ \cdots \\ [r_{b,1}]_\times \\ I\Delta t \end{bmatrix} \alpha_b + N \tag{3.5}$$

Note that an additional accelerometer can't measure angular acceleration's parallel component with $r_(b,i)$, so minimum 2 additional accelerometers are required to measure accurate 3D angular acceleration. Finally, optimal estimation of α_b will obtained by using a pseudo-inverse method as

$$\begin{aligned} \hat{\alpha}_b &= (H^T R^{-1} H)^{-1} H^T R^{-1} Y \\ var(\hat{\alpha}_b) &= (H^T R^{-1} H)^{-1} \end{aligned} \tag{3.6}$$

3.1.5 Wrench estimator

Specific algorithm of proposed wrench estimator will be explained in this section. Like see in (2.4), MBO integerates $\hat{f}_e$ and $\hat{\tau}_e$ implicitly. To discretize it, let's call the integral terms of (2.4) as ρ_f and ρ_τ. Discretized MBO for force is written as

$$\begin{aligned} \hat{\rho}_{t+1} &= \hat{\rho}_t + [\hat{f}_{e,t} + mg + RB_f u]dt \\ \hat{f}_{e,t+1} &= K(mv_{t+1} - \hat{\rho}_{t+1}) \end{aligned} \tag{3.7}$$

And for torque,

$$\begin{aligned}\hat{\rho}_{t+1} &= \hat{\rho}_t + [\hat{\tau}_{e,t}\omega \times (J\omega) + B_{tau}u - r_{cm} \times B_f u]dt \\ \hat{\tau}_{e,t+1} &= K(J\omega_{t+1} - \hat{\rho}_{t+1})\end{aligned} \tag{3.8}$$

It is the same structure with a non-linear Kalman filter. We can write a wrench estimator that propagates state $_t$ recursive summation step about ρ, correct by f_e and τ_e measured with inverse dynamics. more specific explain about each steps are following.

Let's see about force estimation for example. At the propagation step, estimation of ρ_{t-1} and its variance P propagate to ρ_t with

$$(\hat{\rho}_t^-, P_{\rho,t}^-) = UT([1 - K\ dt]\hat{\rho}_{t-1}^- + [Km\hat{v}_{t-1}] + mg + \hat{R}B_f u]dt) \tag{3.9}$$

$\hat{v}$ and $\hat{R}$ are estimated variable from Pixhawk and it is nonlinear. So we have to apply unscented transform to calculate transformed uncertainty.

Next step is correction with inverse dynamics. To correct $\hat{\rho}$, $\hat{f}_e$ and its uncertainty n_{inv} will be measured with $\hat{a}$ as

$$(f_e, Q_{inv}) = UT(m\hat{a} - mg - \hat{R}B_f u) \tag{3.10}$$

With this measurement about f_e, measurement function about ρ is written as

$$\begin{aligned}f_e &= K(mv_t - \rho_t) + n_{inv} \\ &= -K\rho_t + Km\hat{v}_t + n_{inv,v}\end{aligned} \tag{3.11}$$

$n_{inv,v}$ is fused noise of n_{acc} and n_v. We can correct propgated ρ_t^- from (3.9) with obtained f_e from (3.10), as

$$\begin{aligned} K_k &= P_\rho^- H^T (H P_\rho^- H^T + Q_{inv,v})^{-1} \\ \rho_t^+ &= \rho_t^- + K_k (f_e - f_e^-) \\ P_t^+ &= P_t^- - K_k H P_t^- \end{aligned} \tag{3.12}$$

Finally, corrected f_e will be obtained from corrected ρ_t^+.

$$\hat{f}_e^+ = K(m\hat{v}_t - \rho_t^+) \tag{3.13}$$

External torque $\hat{\tau}_e^+$ obtain with the same process, based on angular dynamics on (2.1). Especially angular acceleration $\hat{\alpha}$ use in correction part will be obtained from angular acceleration estimation by the additional accelerometers in 3.1.4. Also, estimated $\hat{\tau}_e$ will be expressed in the link body frame.

3.2 Wrench propagation

In 3.1, external wrench of each link is estimated. By accumulating these estimated wrenches, wrench load at the end effector and each joint can be obtained. And LASDRA for operation [15] are fixed in the base with spherical joint, so the wrench applies to the first link from the base should be measured with FT sensor and accumulate with an estimated external wrench of each link. Equation about accumulate FT sensor measurement at the base and external wrench estimations are

$$\begin{aligned} f_J^i &= f_e^i + f_J^{i-1} \\ \tau_J^i &= \tau_e^i + R_i^T R_{i-1} \tau_J^{i-1} - \vec{L}_c \times [R_i^T f_J^{i-1}] - \vec{L}_c \times [R_i^T f_J^i] \end{aligned} \tag{3.14}$$

f_J^i and τ_J^i are wrench at the joint, which $i+1^{th}$ link applying to i^{th} link. f_e^i and τ_e^i are estiamted external wrench of i^{th} link. R_i is rotation matrix of i^{th} link and $\vec{L}_c$ is position vector from the center to end of the link, for example $[0.5m, 0, 0]$ at LASDRA in our experiment.

Forces f are expressed in world frame and torque τ are expressed in body frame of each link. If we iterate calculation of (3.14) for $i = 1$ to $i = N$, external wrench at the end effector (f_{end}, τ_{end}) will be obtained, which expressed in last link's frame. In $i = 1$, f_J^0 and τ_J^0 is wrench measured from the base FT sensor. If we multiply R_N to obtained τ_{end}, external wrench at the end effector will be expressed in world frame finally.

Chapter 4

Simulation Results

4.1 Simulation setup

Before the experimental verification, the proposed wrench estimator was verified in the simulation environment. The simulation was built in MATLAB for dynamics of 1 link of ODAR as shown in Fig. 4.1. In the simulation for the ODAR, the proposed wrench estimator shows noiseless and faster response than traditional wrench estimators, inverse dynamics, and MBO.

Simulation integrates dynamics with passive midpoint integration (PMI) [17] in 500Hz, which guarantees passivity of simulation. Simulation provides the same sensor data with real experiments explained in 2.1.1. IMU at the center, additional IMUs, and MOCAP. IMU sensor noise and bias drift follow the specification of MPU9250 and MOCAP estimation accuracy was set similar with real word as shown in Table. 4.1

In the simulation, we apply a step-typed external wrench and obtains noised sensor data while ODAR following the sinusoidal trajectory for position and orientation. The proposed angular acceleration estimation and wrench estimation of 3 were applied with provided sensor data, including the built-in EKF of Pixhawk.

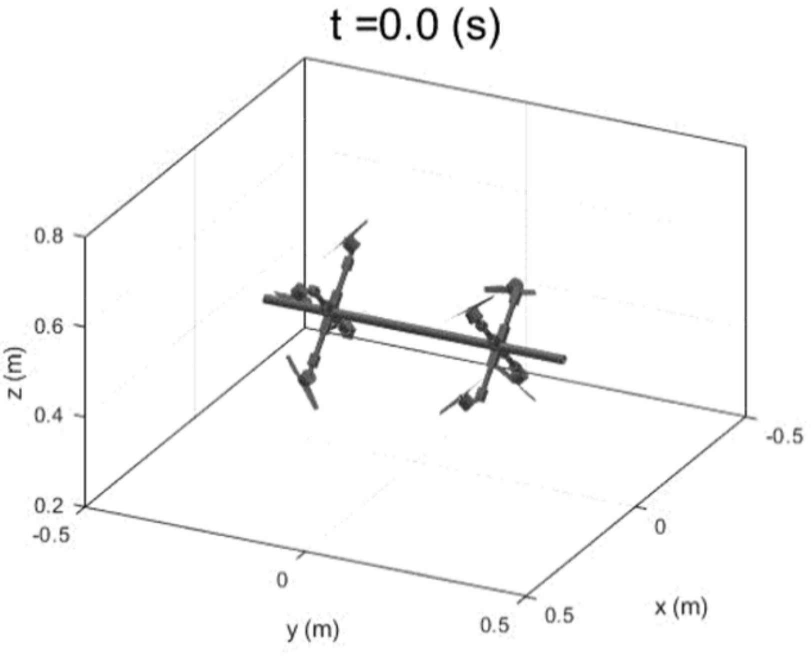

Figure 4.1: ODAR dynamics simulation

Parameters	Noise variance
IMU accelerometer noise (m^2/s^4)	diag($[0.05^2, 0.05^2, 0.05^2]$)
IMU accelerometer bias drift (m^2/s^6)	diag($[0.0005^2, 0.0005^2, 0.0005^2]$)
IMU gyroscope noise (rad^2/s^2)	diag($[0.01^2, 0.01^2, 0.01^2]$)
IMU gyroscope bias drift (rad^2/s^4)	diag($[0.000009^2, 0.000009^2, 0.000009^2]$)
MOCAP position noise (m^2)	diag($[0.001^2, 0.001^2, 0.001^2]$)
MOCAP orientation noise (rad^2)	diag($[0.03^2, 0.03^2, 0.03^2]$)

Table 4.1: Sensor noise assumed in simulation

Estimation proceeds in the same bandwidth with the real world, Pixhawk built-in EKF in 500Hz and the wrench estimator in 100Hz. And to give identification error, 10% reduced momentum of inertia was used in the estimator.

Estimated results for angular acceleration and external wrench were compared with ground truth data from the simulation. Also, wrench estimation with MBO and inverse dynamics were proceeded to compared with the proposed wrench estimator.

4.2 Angular acceleration estimation

Simulation results for acceleration estimation are following. Data from the IMU of centered pixhawk and 2 additional IMUs place at the end of the link ([0.5m; 0; 0], [0.25m; 0; 0.25m] in the acceleration estimation.

Fig. 4.2 shows angular acceleration results of the proposed estimator and simple differential of angular velocity. Simply differentiated angular velocity shows

$6.8 rad/s^2$ of RMS error. it is an extremely large error to use at the wrench estimator. But the proposed estimator with additional IMUs shows $0.56 rad/s^2$ of RMS error. We can see the proposed angular acceleration estimation method providing much more accurate estimation for the angular acceleration.

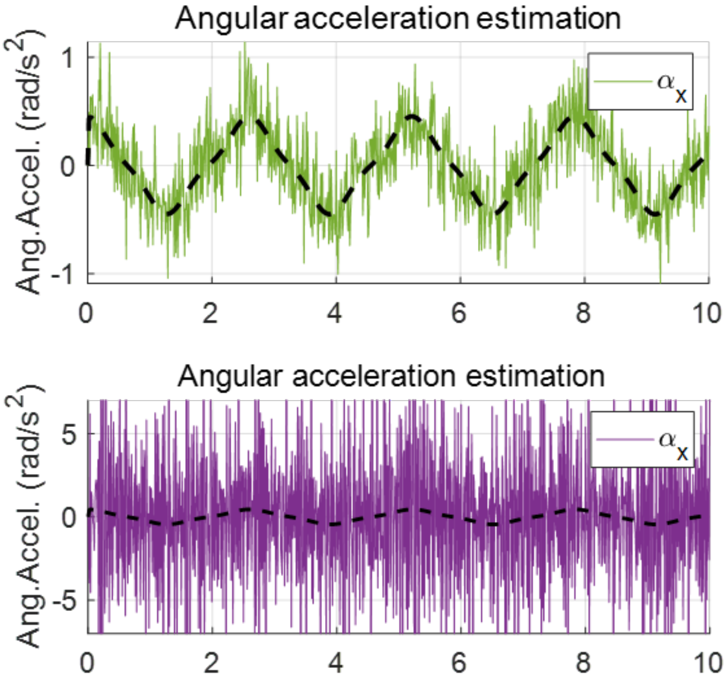

FIGURE 4.2: Angular acceleration estimation results

4.3 External wrench estimation

Simulation results for 3 types of wrench estimators (proposed, MBO, and inverse dynamics) are shown in Fig. 4.3. Estimation for force of z direction and torque of x direction are presented.

Like written in 2.2, inverse dynamics shows un-delayed but noisy estimation, with $0.13N$ of RMS error. MBO shows noiseless but delayed estimation, with 0.02 N of RMS error and $0.22sec$ of 10% settling time. The proposed estimator shows more less delay than MBO and noiseless than inverse dynamics, with $0.04N$ of RMS error and $0.06sec$ of 10% settling time. This results verifies delay reducing with optimally fusing acceleration data to MBO. In the next section, experimental results in the real world will be presented.

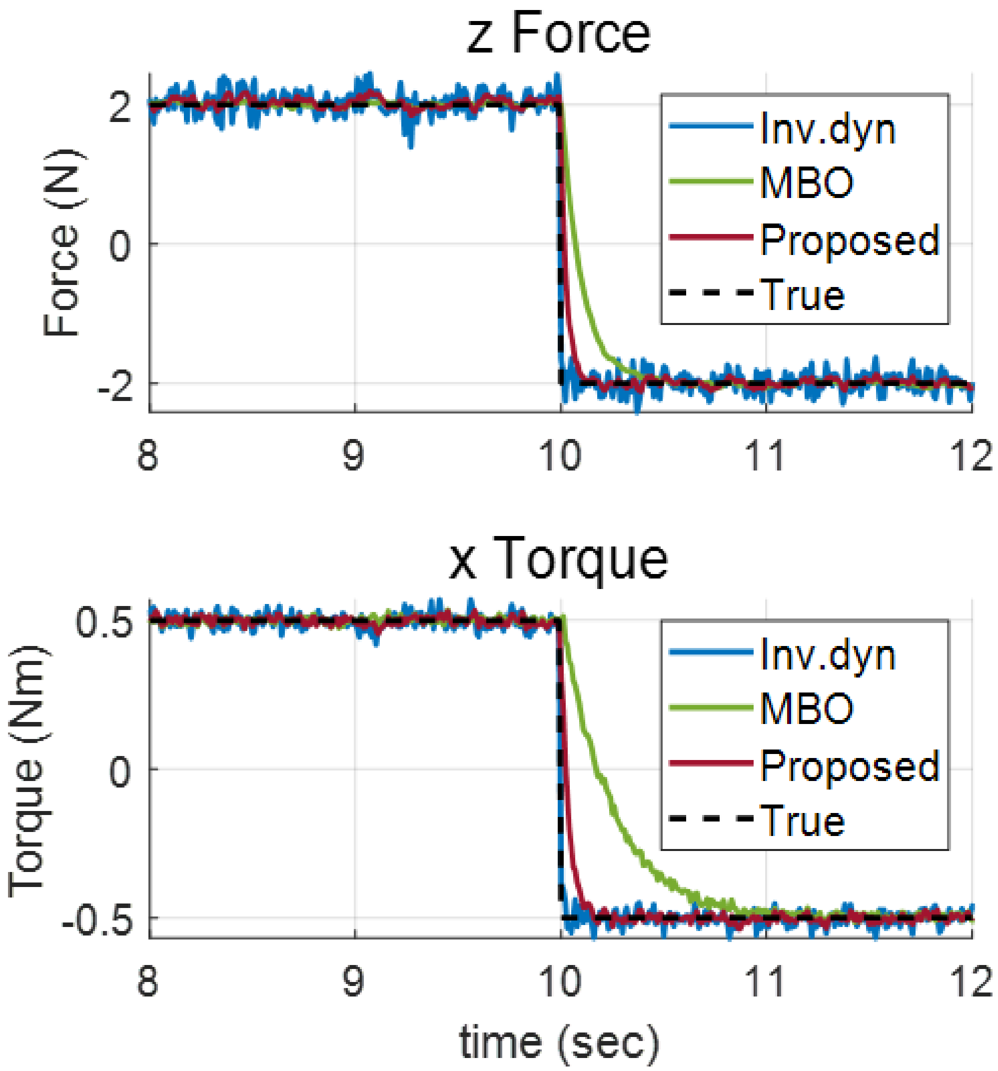

FIGURE 4.3: Wrench estimation results

Chapter 5

Experimental Results

5.1 Experiment setup

To verify the proposed wrench estimator in experiments, 3-link LASDRA and sensors are constructed as shown in Fig. 5.1. Pixhawk uses IMU (MPU9250) and MOCAP data (Optitrack) to estimate its pose and velocity with EKF. And 2 additional IMUs of each link are connected with RaspberryPi directly as shown in Fig. 3.1. FT sensor sensors to measure the wrench at the base are mounted between the first link and the base. The external wrench at the end is measured with another FT sensor.

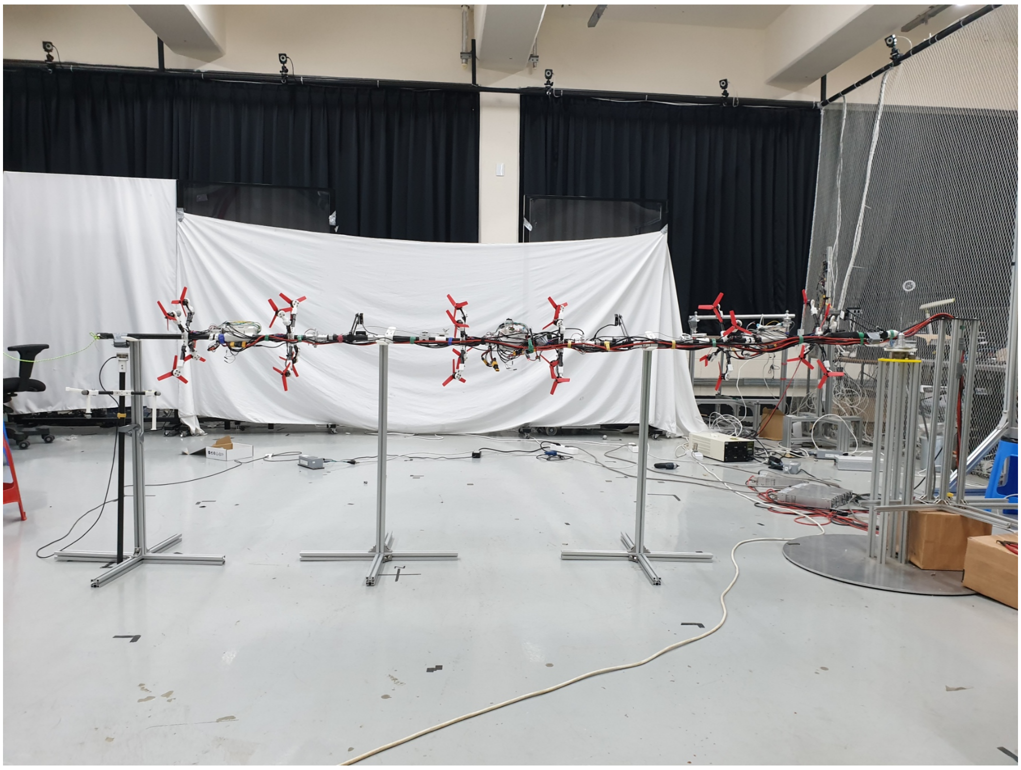

Figure 5.1: 3-link LASDRA

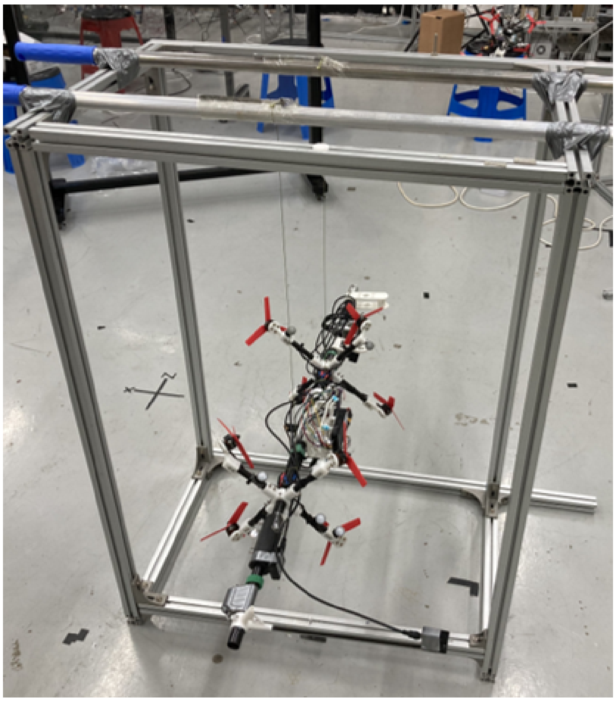

FIGURE 5.2: Momentum of inertia identification

5.1.1 LASDRA setup

LASDRA used in the experiment use MPU9250 IMU and Optitrack MOCAP. Phidget IMU [1] are used for additional IMU, which can directly connected with RaspberryPi by USB. The IMUs are attached with gel to alleviate the noise of the vibration of propellers.

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[1] https://www.phidgets.com

	Link 1	Link 2	Link 3
M (kg)	2.09	2.114	1.598
I_{xx} $(kg\ m^2)$	0.0121	0.1715	0.1664
I_{yy} $(kg\ m^2)$	0.0121	0.1229	0.1262
I_{zz} $(kg\ m^2)$	0.0106	0.1120	0.1087

TABLE 5.1: Identification results of each link

Accurate identification of mass and momentum of inertia of each link is important for accurate wrench estimation. Mass of each link is measured by a scale and momentum of inertia is calculated by measure the frequency of a bifilar torsional pendulum as shown in Fig. 5.2. The measured mass and momentum of inertia of each link are shown in Table. 5.1.

5.1.2 FT sensors setup

2 FT sensors are used in the experiments. ATI gamma FT sensor is mounted at the base. The sensor and base joint are connected with the gel to alleviate noise of the vibration, as shown in Fig.5.3.

ATI mini FT sensor is mounted at the independent handle as shown in Fig. 5.4. While LASDRA is hovering in a specific configuration, an external wrench is applied to the end effector with the handle as shown in Fig. 5.6. Ft sensor at the

FIGURE 5.3: FT sensor at the base

handle measures the ground truth external wrench applied at the end effector. But a measured wrench is expressed in the body frame of the handle, so MOCAP markers are attached to the handle and measure the real-time pose of the handle. By multiplying the rotation matrix of the handle to the measured wrench, the ground truth external wrench expressed in MOCAP frame is obtained.

The gel tape are attached on the end effector as shown in Fig. 5.5 to alleviate noise of the vibration.

FIGURE 5.4: FT sensor with the handle

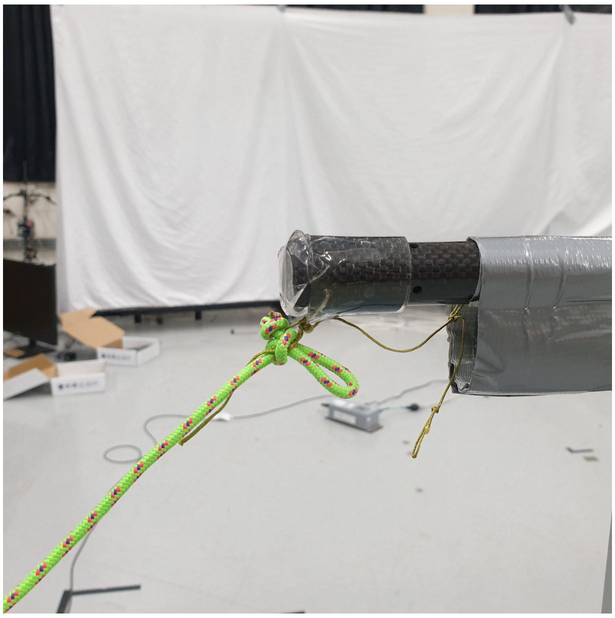

Figure 5.5: Gel on the end effector

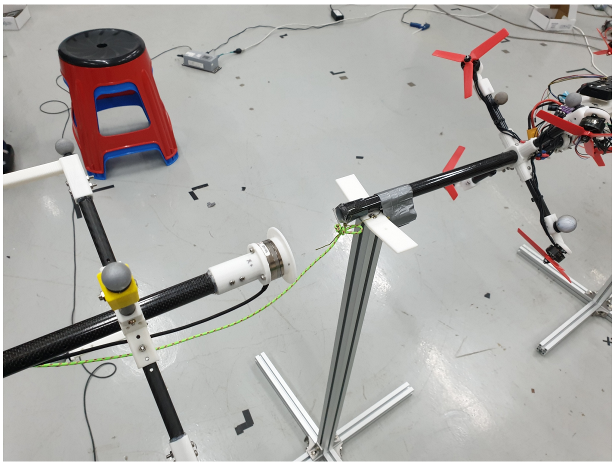

Figure 5.6: Pushing end effector with handle

5.1.3 Experiments scenario

In the experiments, the external force is applied at the end effector while LASDRA hovering in 3 different configurations as shown in Fig. 5.7.3 directions of external force are applied at the end effector as shown in Fig. 5.8.

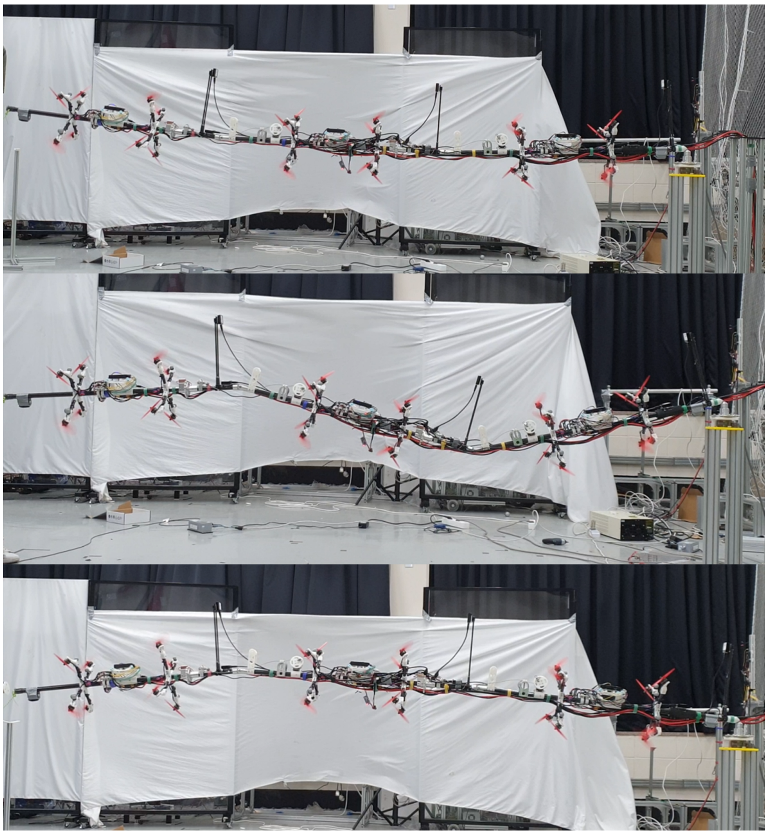

FIGURE 5.7: 3 configurations of LASDRA. Straight, zigzag, and middle raised.

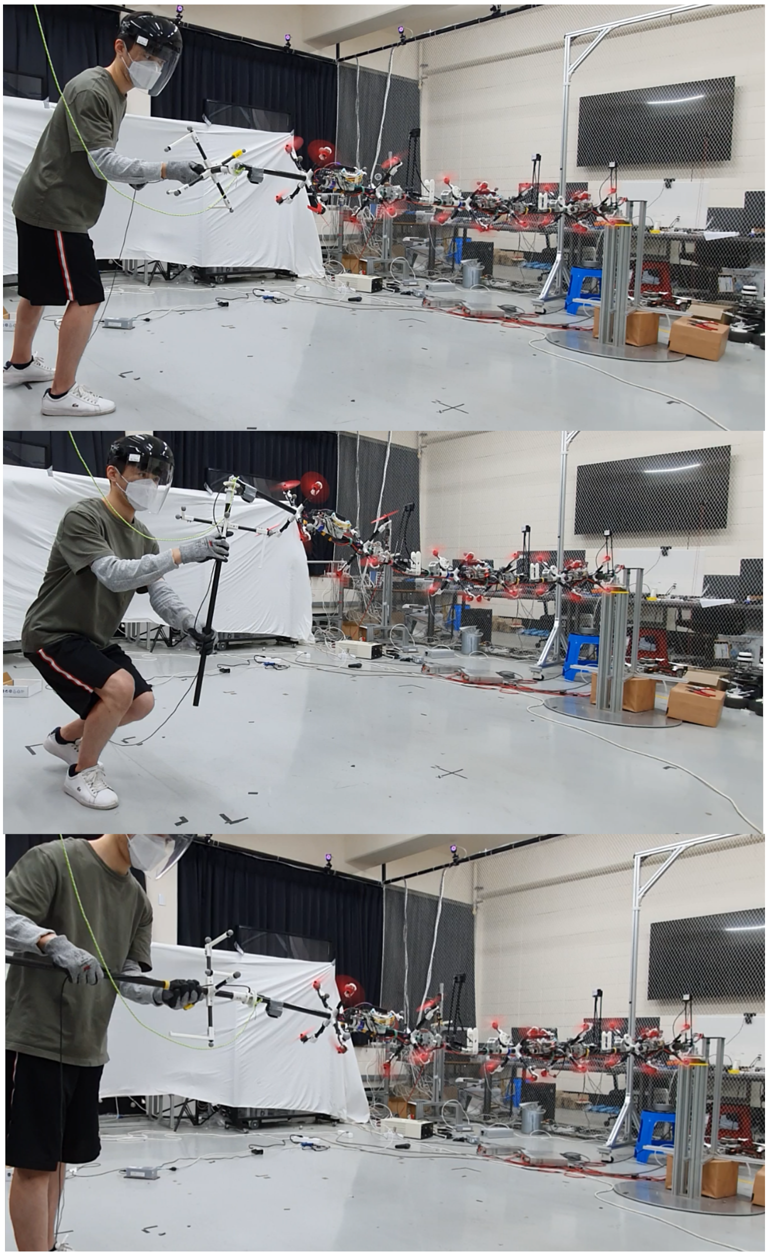

Figure 5.8: 3 directions of pushing end effector

5.2 Wrench estimation results

In this section, experiment results about the wrench estimator are presented. The external wrench of LASDRA was estimated with 3 types of wrench estimators (proposed, MBO, inv dynamics) and compared with ground truth. Ft sensor data received in 400Hz, IMU data received in 50Hz, and the estimator run in 100Hz.

Fig. 5.9 - 5.11 are wrench estimation results with the proposed wrench estimator at configuration of straight, zigzag, middle raised. We can the external wrench are estimated as same as ground truth in variable configurations. But bias of y direction force estimation is increasing slowly in the time. It is because of unmodeled tension of the power lines shown in Fig. 5.3. To make unmodeled tension of the powerline to zero, we tie power line next to the pillar. But power line bent at the flying and additional tension is generated and make biased error.

And also results about MBO and inverse dynamics are shown in Fig. 5.12, 5.13,. Inverse dynamics is showing much noisy estimation compare to MBO. And MBO is showing a similar delay with the proposed wrench esitimator. It is because external wrench was slowly applied to LASDRA, because of its control stability.

So the proposed wrench esimator has verified through the experiment with 3-link LASDRA,

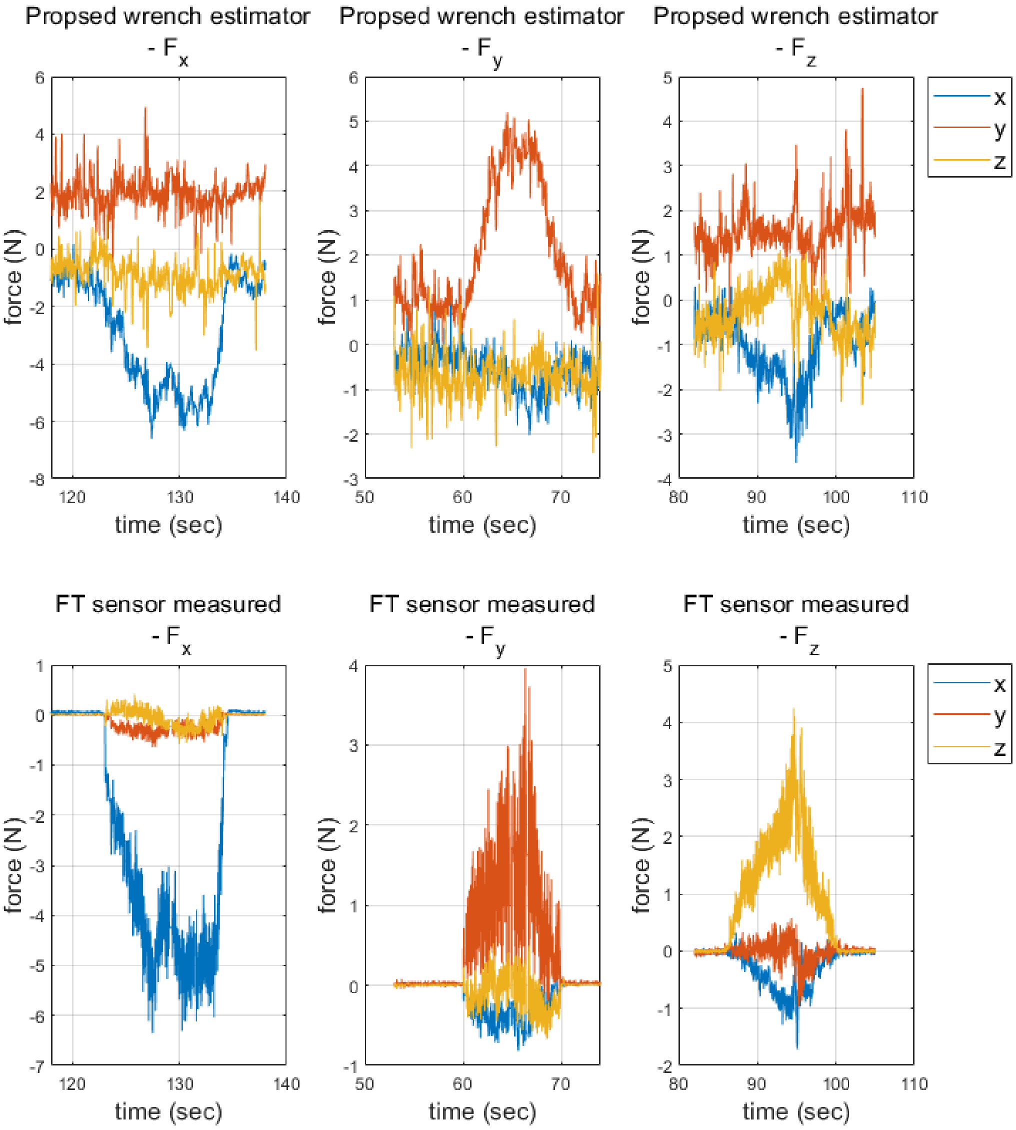

Figure 5.9: Estimation result of proposed wrench estimator at straight configuration

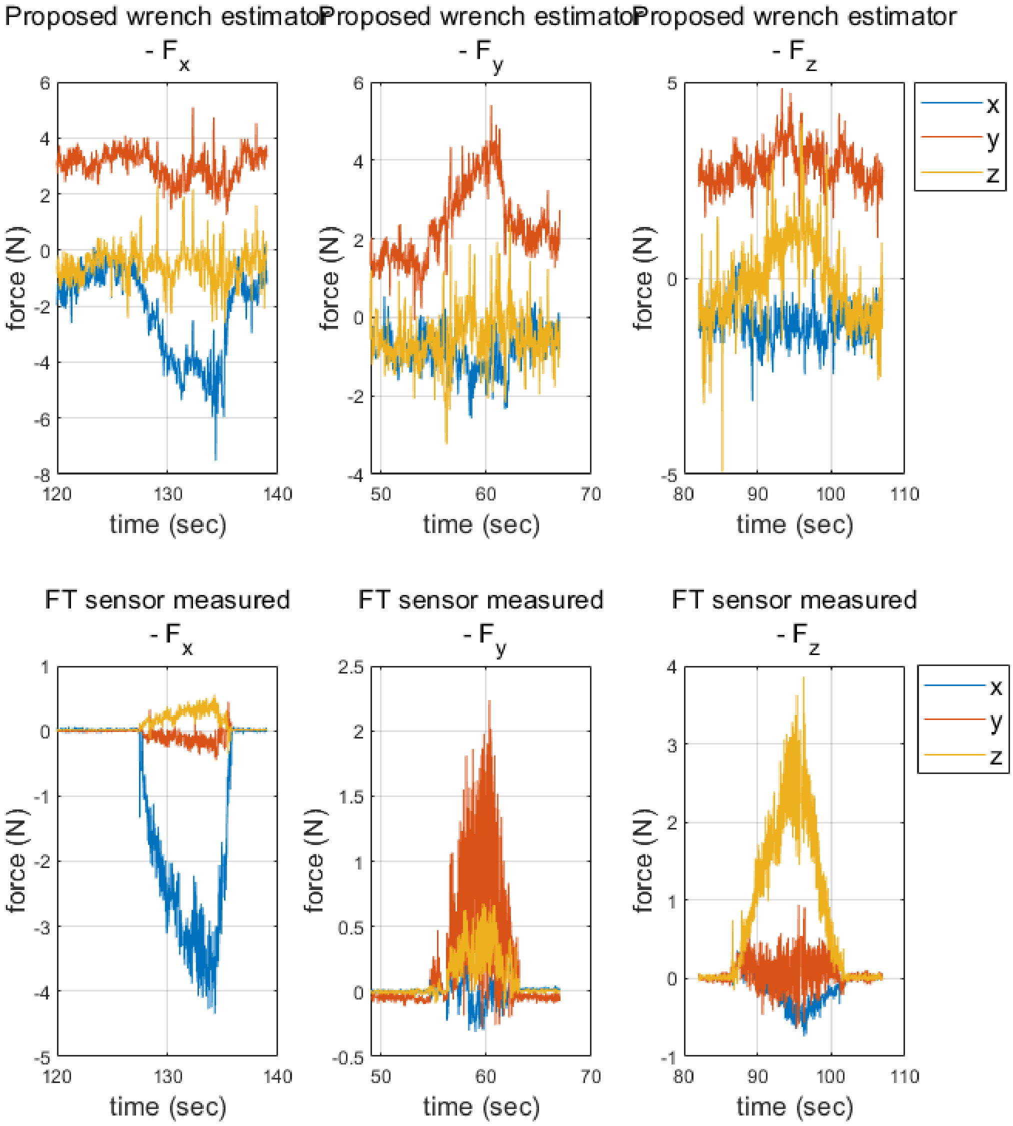

Figure 5.10: Estimation result of proposed wrench estimator at zigzag configuration

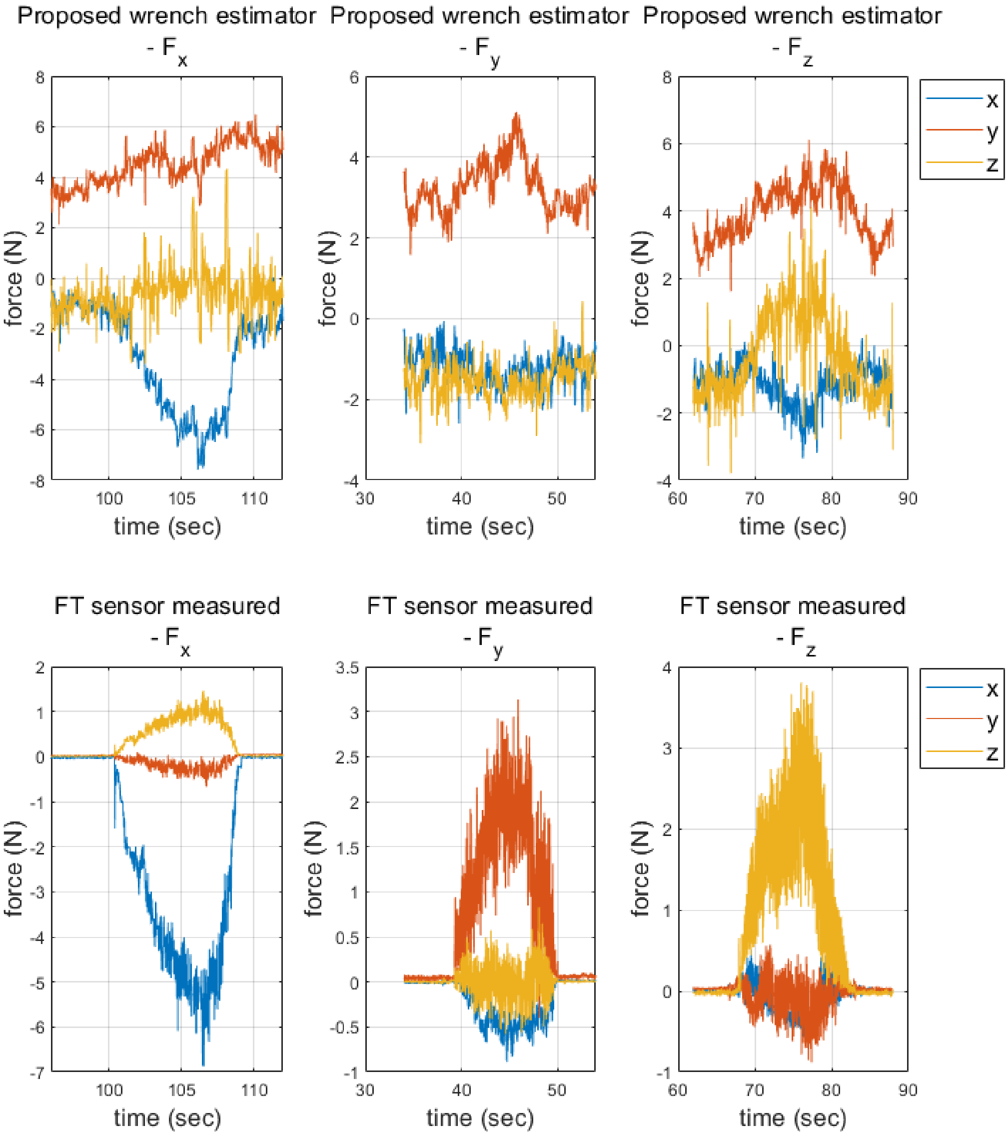

Figure 5.11: Estimation result of proposed wrench estimator at middle raised configuration

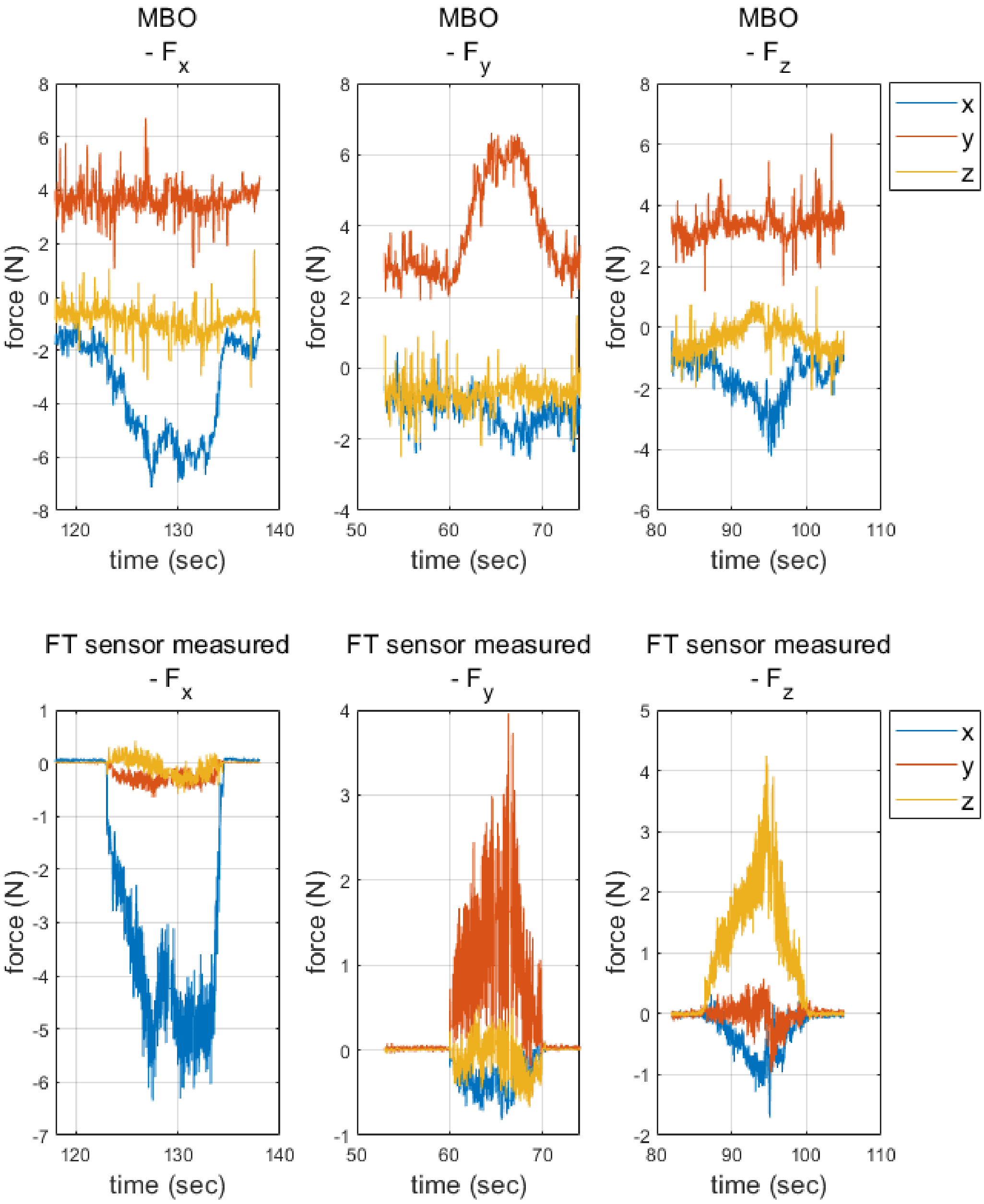

FIGURE 5.12: Estimation result of MBO at straight configuration

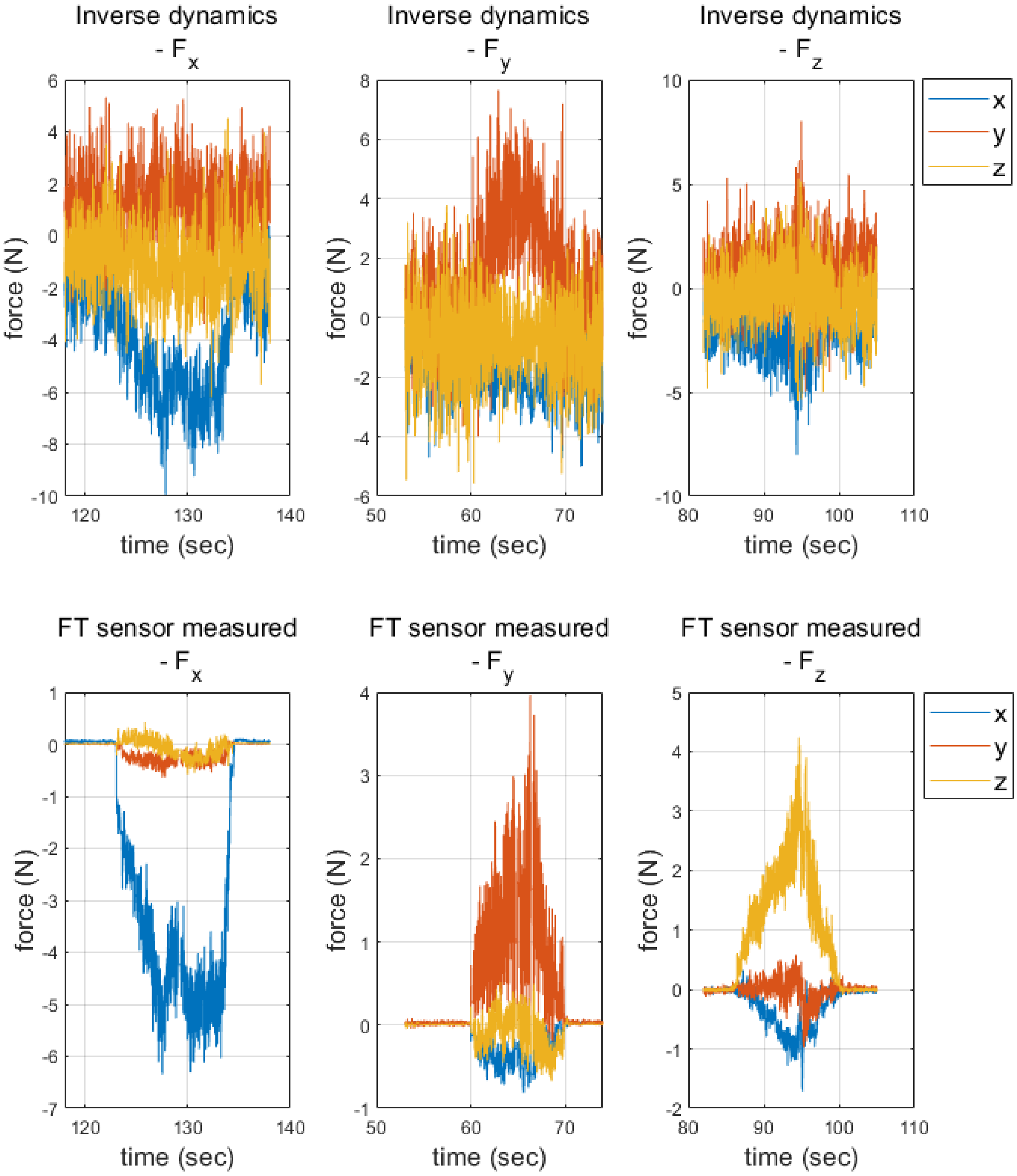

FIGURE 5.13: Estimation result of inverse dynamics at straight configuration

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this paper, contact wrench estimator using distributed IMUs for LASDRA (Large-size Aerial Skeleton with Distributed Rotor Actuation) and simulation verification have proceeded. Conventional robot arm measures acceleration by differentiating encoder information twice. Twice differentiated acceleration is too noisy to use at wrench estimation. So momentum based observer are conventionally used at wrench estimation, which recursively integrates velocity. But it has a delay at dynamically changing external wrench because it is the form of the observer.

Multiple, distributed IMUs of LADSRA can solve this limitation. LASDRA measure acceleration directly with IMUs, so by fuse acceleration information to momentum based observer, a delay will be reduced. The proposed wrench estimator fuses acceleration information with Kalman Filer form, which uses momentum based observer as propagation step and inverse dynamics as the correction step. The proposed estimator fuses momentum based observer and inverse dynamics corresponding to its uncertainties.

To verify the proposed wrench estimator, PMI based ODAR simulation is built. Realistic sensor noised are assumed and 10% of identification error of momentum of inertia are applied. Through the simulation, the proposed wrench estimator shows reduced delay than momentum based observer and is less noisy than inverse dynamics.

Experimental verification in the real world also proceeded. 3-link LASDRA with MOCAP is built. FT sensor has mounted on the base to measure wrench between the base and the first link. 3 directions of external force were applied at the end effector while LASDRA hovering in 3 different configurations. Ground truth of external wrench is obtained by FT sensor mounted on the MOCAP tracked handle. The measured external wrench is transformed to MOCAP frame. Through the experiments, the external wrench was estimated similar to ground truth by FT sensor. But y direction force estimation shows 2N of bias because of the unmodeled tension of the powerline. And external wrench was changed slowly to guarantee the stability of control, momentum based observer shows similar behavior with the proposed wrench estimator.

Finally, we develop a novel wrench estimator that has reduced delay than conventional momentum based observer and verify in simulation and real experiments.

6.2 Future work

The proposed wrench estimator can also be applied to a typical robot arm by attaching IMUs to it. It will make a faster response that momentum based observer same as at LASDRA. Also, it will show a more accurate wrench estimation than at the LASDRA because it has much fewer vibrations than aerial platforms.

In the perspective of control, force-torque control of LASDRA is possible by using the proposed wrench estimator. And the proposed wrench estimator loaded the wrench of each joint because of its distributed structure. By using an estimated joint loaded wrench, a control algorithm alleviates the load of the joint when the joints are locked.

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요약

본 논문에서는 분산배치된 다중 IMU를 활용한 공중작업용 분산로터기반 거대 스켈레톤 시스템(large-size aerial skeleton system with distributed rotor actuation (LASDRA))의 외력 추정 기법을 제시하였다. 속도 정보만을 사용하는 기존의 모멘텀기반 외력 관측기를 다중/분산 IMU에서 측정된 가속도 정보를 융합하여 외력추정의 정확도와 성능을 향상 시켰으며, 각가속도 또한 다중 IMU 신호를 활용 추정하여 외력 토크 추정 정확도 또한 향상 시켰다. 제시된 외력 추정기는 시뮬레이션 상에서 모멘텀기반 외력 관측기와 함께 적용되어 가속도 정보를 사용하여 외력 추정의 딜레이가 줄어드는것을 확인하였으며, 3개 링크로 구성된 LASDRA의 외력을 추정하는 실험을 진행하여 실제 환경에서도 사용 가능함을 확인하였다.

주요어: Key Words : Sensor fusion, Wrench estimation, Unscented Kalman filter, Aerial manipulation
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2021년 8월

이하선