Shoulder and Elbow Joint Angle Tracking With Inertial Sensors

El-Gohary, M., & McNames, J. (2012). Shoulder and elbow joint angle tracking with inertial sensors. IEEE Transactions on Biomedical Engineering, 59(9), 2635–2641. https://doi.org/10.1109/TBME.2012.2208750

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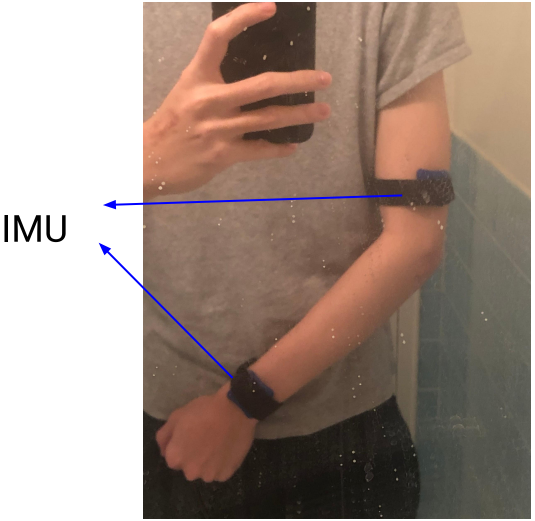
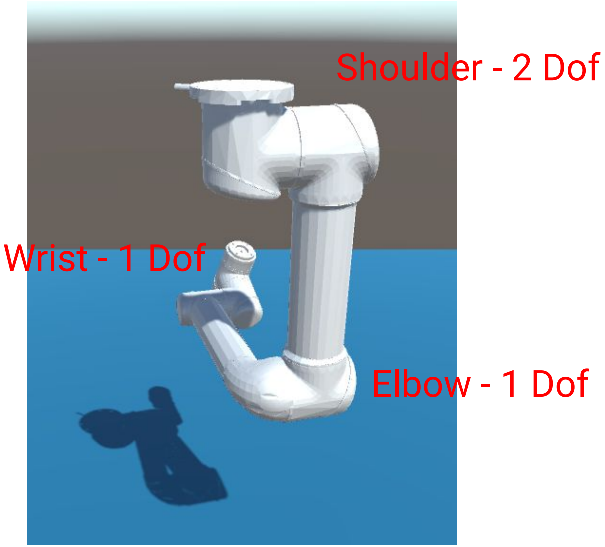
Statement of project



2-IMU system

Joint angles

Kinematics



Virtual robot arm demo

https://github.com/qian256/ur5_unity

Summary of problem & key results

Problem:

- Continuously estimate the angles of human shoulder and elbow using 2 IMUs

Key Results:

- Computed joint angles using inertial sensor (IMU)
- Validation joint angles using optical tracker

Significance of key result

- Good agreement between inertial tracker and optical tracker for both regular and fast-speed movement of the arm.
- Average correlation coefficient r > 0.95
- RMS angle error < 6.5 deg
- Peak error < 9.8 deg

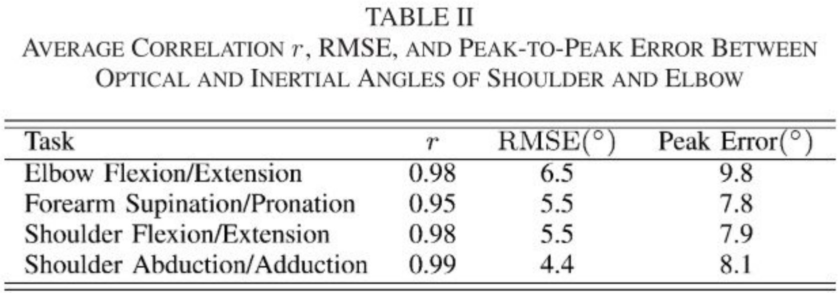


TABLE II

AVERAGE CORRELATION r, RMSE, AND PEAK-TO-PEAK ERROR BETWEEN OPTICAL AND INERTIAL ANGLES OF SHOULDER AND ELBOW

Task	r	RMSE($^\circ$)	Peak Error($^\circ$)
Elbow Flexion/Extension	0.98	6.5	9.8
Forearm Supination/Pronation	0.95	5.5	7.8
Shoulder Flexion/Extension	0.98	5.5	7.9
Shoulder Abduction/Adduction	0.99	4.4	8.1

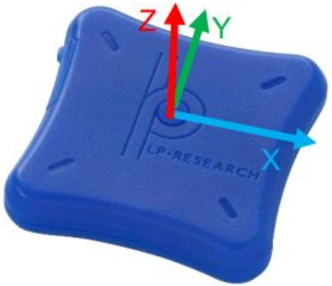
[4]: El-Gohary, et al., 2012

Why this paper?

Paper	CIS 2 Project
Measures shoulder and elbow joint angles using 2 IMUs	Measures shoulder and elbow joint angles using 2 IMUs
Validates computed joint angles with optical tracker	Validates computed joint angles in Unity with virtual robot arm

Background - IMU

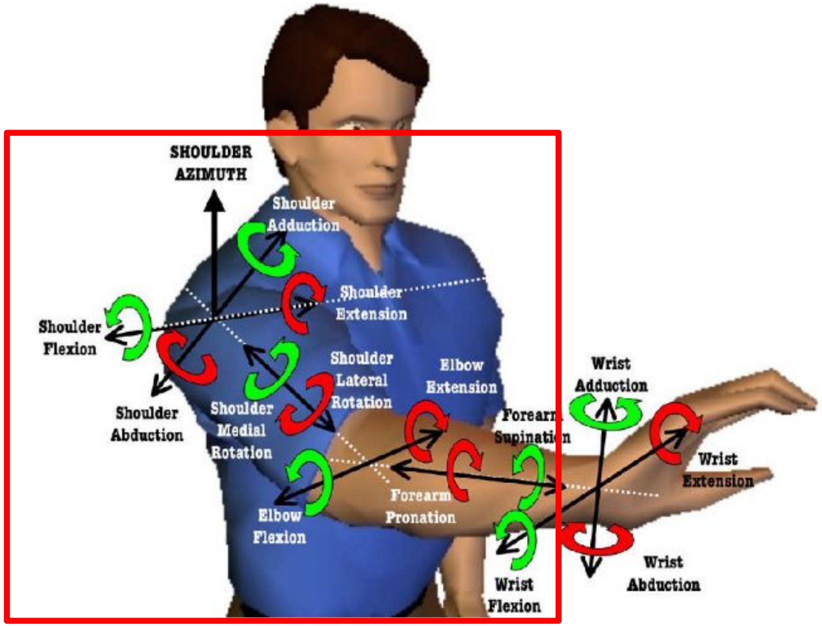
- Low cost MEMS* systems
- 3-axis Gyroscope - angular velocity
- 3-axis Accelerometer - linear acceleration
- 3-axis Magnetometer - magnetic field strength
- Internal sensor fusion: gyro + acc + mag / gyro + acc
- Sensor fusion output: 3DOF orientation in body fixed frame of the IMU (Euler angles/Quaternions)



https://lp-research.com/wp-content/uploads/2020/03/20200310LpmsB2HardwareManual.pdf

*: microelectromechanical

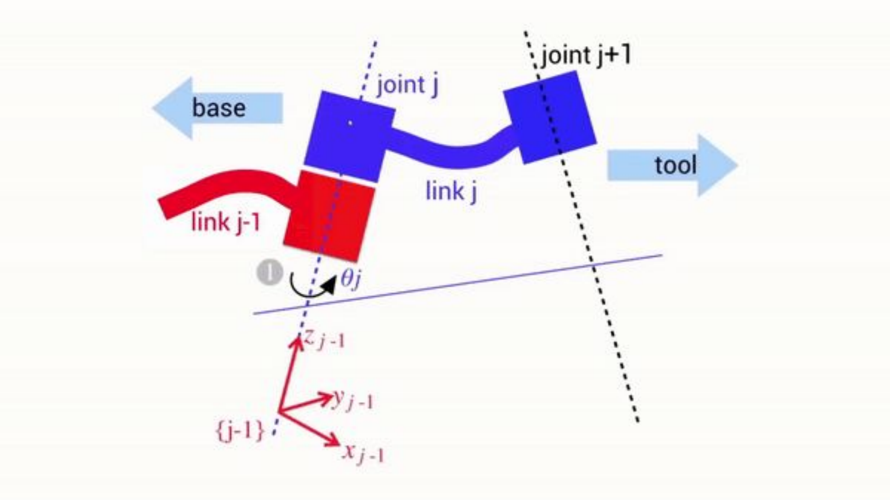
Background - Human Arm Joint Angles



[5]: D. Naidu, et al., 2011

Joint	DOF
Shoulder	3
Elbow	2
Wrist	2

Background - DH Parameters



[1]: https://robotacademy.net.au/lesson/denavit-hartenberg-notation/

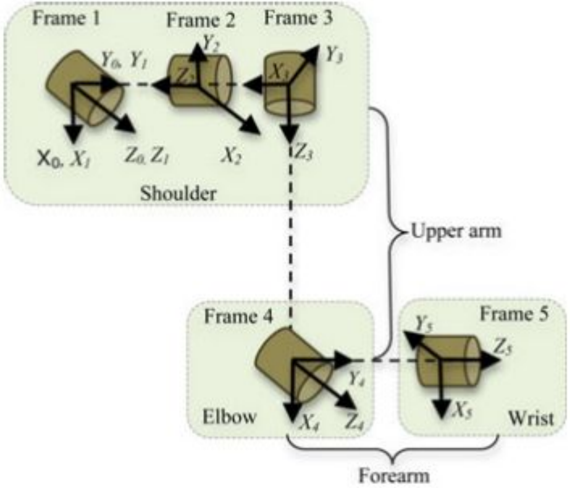
$$ {}^{i-1}A_i = Rot_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} Rot_{x,\alpha_i} $$

4 “Basic” transformation parameters

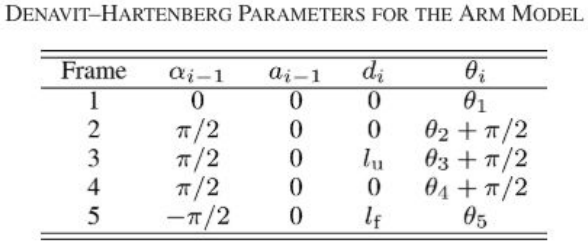
- rotate around the zj-1 axis by an angle θi
- translate along zj-1 axis by a distance di
- translate along the new x axis by a distance aj
- rotate around the new x axis by an angle αj

[2]:http://www.aeromech.usyd.edu.au/MTRX4700/Course_Documents/material/lectures/L2_Kinematics_Dynamics_2013.pdf

Paper – Human Arm Kinematics



[4]: El-Gohary, et al., 2012



DENAVIT–HARTENBERG PARAMETERS FOR THE ARM MODEL

Frame	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$\pi/2$	0	0	$\theta_2 + \pi/2$
3	$\pi/2$	0	l_u	$\theta_3 + \pi/2$
4	$\pi/2$	0	0	$\theta_4 + \pi/2$
5	$-\pi/2$	0	l_f	θ_5

For shoulder joint:
“When a joint has n-DOFs, it can be modeled as n joints of one DOF connected with n − 1 links of zero length” - El-Gohary, et al., 2012

Paper – Experimental setup

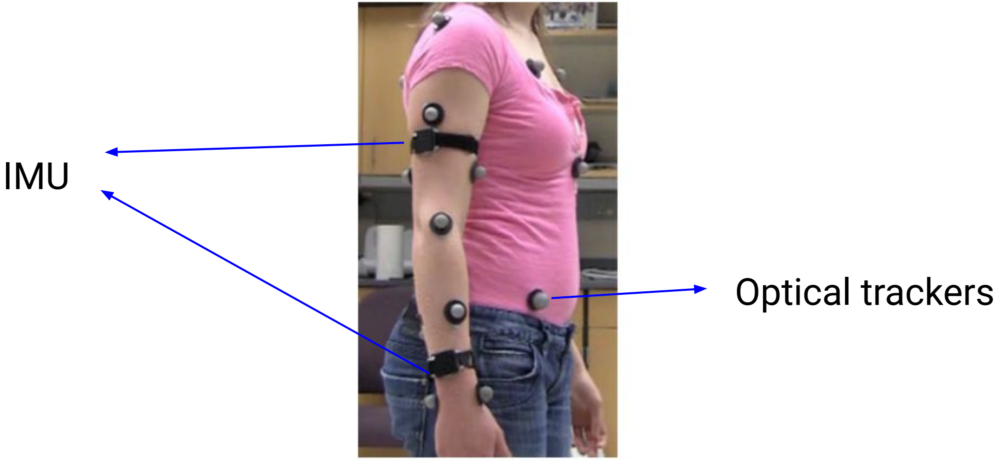


Fig. 2. Reflective markers and Opal inertial sensors (APDM, Inc.) placement on the arm of one of the subjects.

[4]: El-Gohary, et al., 2012

Paper – Kalman Filter

State estimation $x(n+1) = f_n\left[x(n), u(n)\right]$

Observation $y(n) = h_n\left[x(n), v(n)\right]$

State estimation

$$\theta_i(n+1) = \theta_i(n) + T_s\dot{\theta}_i(n) + \frac{1}{2}T_s^2\ddot{\theta}_i(n)$$
$$\dot{\theta}_i(n+1) = \dot{\theta}_i(n) + T_s\ddot{\theta}_i(n)$$
$$\ddot{\theta}_i(n+1) = \alpha\ddot{\theta}_i(n) + u_{\ddot{\theta}_i}(n)$$

where $i = \{1, \ldots, 5\}$ of the five angles, $\theta_i(n)$ is the ith angle at time n, $\dot{\theta}_i$ is the angular velocity, $\ddot{\theta}_i$ is the angular acceleration, $u_{\ddot{\theta}_i}(n)$ is a white noise process with zero mean, α is a process model parameter, and $T_s = 1/f_s$ is the sampling period.

KF output: posterior estimate (after measurement correction) of the five joint angles

Observation

$$\dot{\omega}_z = \dot{\theta}_3 + \dot{\theta}_1 s\theta_2$$
$$\dot{\omega}_x = \dot{\theta}_1 c\theta_2 s\theta_3 - \dot{\theta}_2 c\theta_3$$
$$\dot{\omega}_y = \dot{\theta}_1 c\theta_2 c\theta_3 + \dot{\theta}_2 s\theta_3$$
$$\dot{v}_x = -l_u[\dot{\theta}_1^2 c\theta_2^2 + \dot{\theta}_2^2] - gc\theta_1 c\theta_2$$
$$\dot{v}_y = l_u[c\theta_2 s\theta_2 s\theta_3\dot{\theta}_1^2 - 2\dot{\theta}_2 c\theta_3 s\theta_2\dot{\theta}_1 + \ddot{\theta}_2 s\theta_3 + \ddot{\theta}_1 c\theta_2 c\theta_3] + g[c\theta_3 s\theta_1 + c\theta_1 s\theta_2 s\theta_3]$$
$$\dot{v}_z = l_u[c\theta_2 c\theta_3 s\theta_2\dot{\theta}_1^2 + 2\dot{\theta}_2 s\theta_2 s\theta_3\dot{\theta}_1 + \ddot{\theta}_2 c\theta_3 - \ddot{\theta}_1 c\theta_2 s\theta_3] - g[s\theta_1 s\theta_3 + c\theta_1 c\theta_3 s\theta_2]$$

Subject specific:
Better KF than IMU's internal KF?

ω: angular velocity from gyroscope
v-dot: linear acceleration from accelerometer

[4]: El-Gohary, et al., 2012

Paper – Results

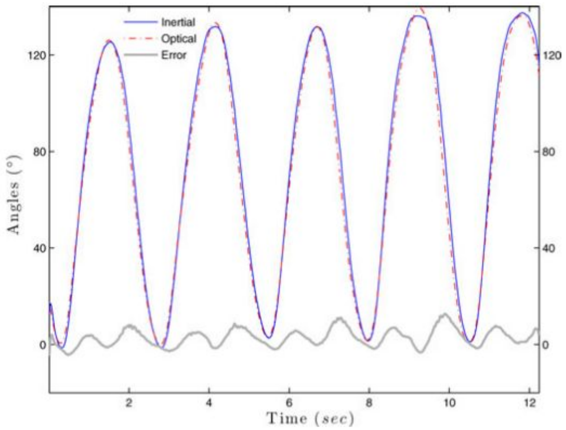


Fig. 5. Shoulder abduction/adduction angle estimates by the optical system (dashed line) compared to inertial angles estimate (solid line), and the error in gray.

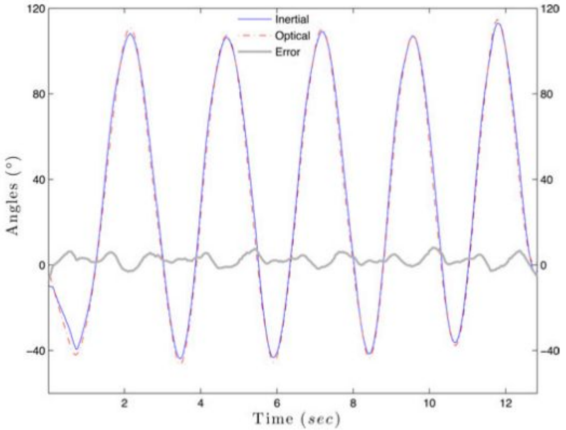


Fig. 6. Shoulder flexion/extension estimates by the optical system (dashed line) compared to inertial angles estimate (solid line), and the error in gray.

Result of shoulder angles - abduction/adduction, and flexion/extension

[4]: El-Gohary, et al., 2012

Paper – Results

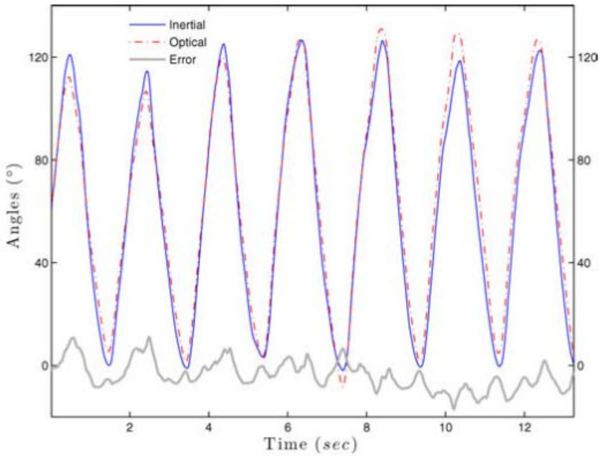


Fig. 4. Forearm supination/pronation estimates by the optical system (dashed line) compared to inertial angles estimate (solid line), and the error in gray.

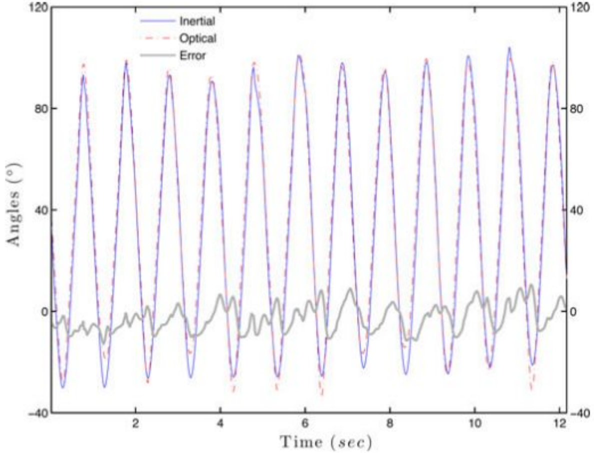


Fig. 7. Elbow flexion/extension during fast arm movement. Inertial estimates (solid line) compared to estimates from the optical system (dashed line).

Result of forearm angles - forearm supination/pronation, and elbow flexion/extension

[4]: El-Gohary, et al., 2012

Assessment

Pros

- Detailed Kalman Filter model
- High correlation between inertial(post-KF) output and optical tracker output
- Longer assessment period than other IMU based work (2-min)

Cons

- No Shoulder internal/external rotation validation data and did not explain why
- Did not explain why IMU’s integrated KF is not sufficient, given their sensor are ~$4k a piece

Relevance to project

- Real-time joint angle tracking, and generalized to track any limb movement
- Assumption is the same: the trunk of the human subject must remain perpendicular to the ground
- Sensor placement is a good starting point for CIS 2 project
- Further study potential: does the IMU drift in Z-axis really affect human-in-the-loop operation such as teleoperation surgery? (comparison between IMU internal KF and subject specific KF)

Conclusion

- Useful theory of arm D-H parameter
- Solid summary of other relevant inertial tracking work
- Application specific yet generalized enough for other limb tracking
- Very relevant to CIS 2 project

Reference

1. D-H https://robotacademy.net.au/lesson/denavit-hartenberg-notation/
2. D-H http://www.aeromech.usyd.edu.au/MTRX4700/Course_Documents/material/lectures/L2_Kinematics_Dynamics_2013.pdf
3. IMU https://stanford.edu/class/ee267/lectures/lecture9.pdf
4. El-Gohary, M., & McNames, J. (2012). Shoulder and elbow joint angle tracking with inertial sensors. IEEE Transactions on Biomedical Engineering, 59(9), 2635–2641. https://doi.org/10.1109/TBME.2012.2208750
5. Naidu, D., Stopforth, R., Bright, G., & Davrajh, S. (2011). A 7 DOF exoskeleton arm: Shoulder, elbow, wrist and hand mechanism for assistance to upper limb disabled individuals. IEEE AFRICON Conference, (September), 1–6. https://doi.org/10.1109/AFRCON.2011.6072065

Backup: Statement of project

- Design a wearable system that
  - Captures surgeon's arm motion in 4DOF at tool (palm)
  - Can control state-of-the-art robot such as UR3 or dVRK - use Unity for virtual demo
  - Has high precision in position control of the slave robot
  - Has a similar workspace as the Da Vinci's MTM
  - Has a way to recognize surgeon's intention to engage/disengage with the system (rules of engagement)