MEMS inertial sensors for load monitoring of wind turbine blades

Aubryn Cooperman and Marcias Martinez

Motivation

Why is load monitoring needed on wind turbines?

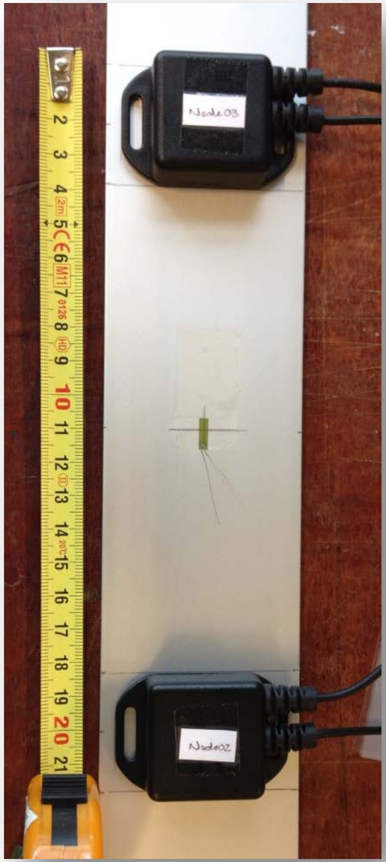
- Key trends:
  - Larger turbines
  - Offshore wind farms
- Higher operations & maintenance costs
  - Harsh environment
  - Limited access to wind farms
- Monitoring of turbines enables condition-based maintenance

Sensors

Micro-Electro-Mechanical Systems

- Dimensions: 35 mm × 35 mm × 15 mm
- Sensors: triaxial accelerometers, gyroscopes and magnetometers

Sensor	Range	Resolution
Accelerometer	±2 g	190 µg ± 5%
Gyroscope	± 2000°/s	0.07°/s
Magnetometer	± 100 µT	0.1 µT

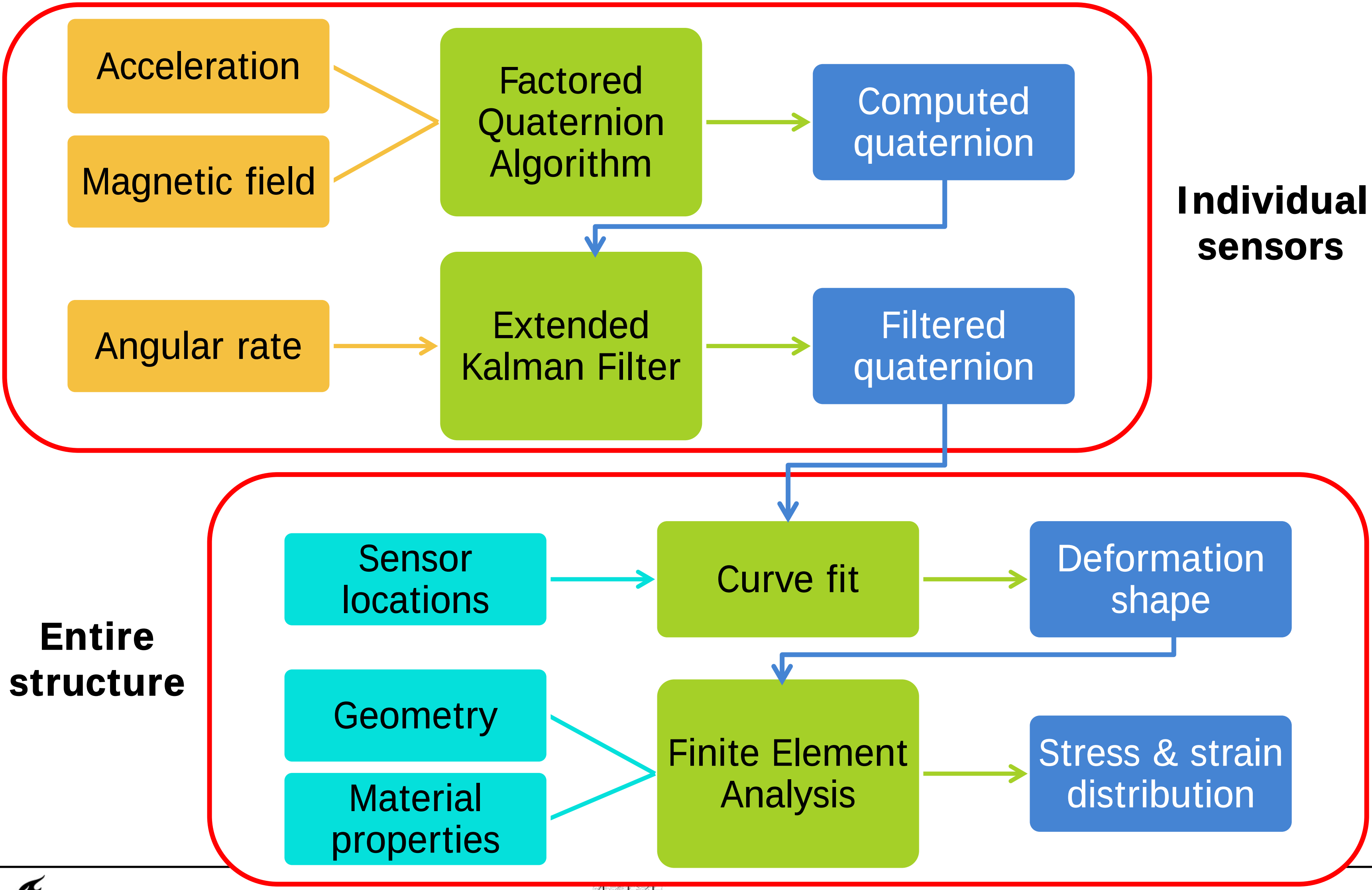


Objective

Use MEMS sensors to:

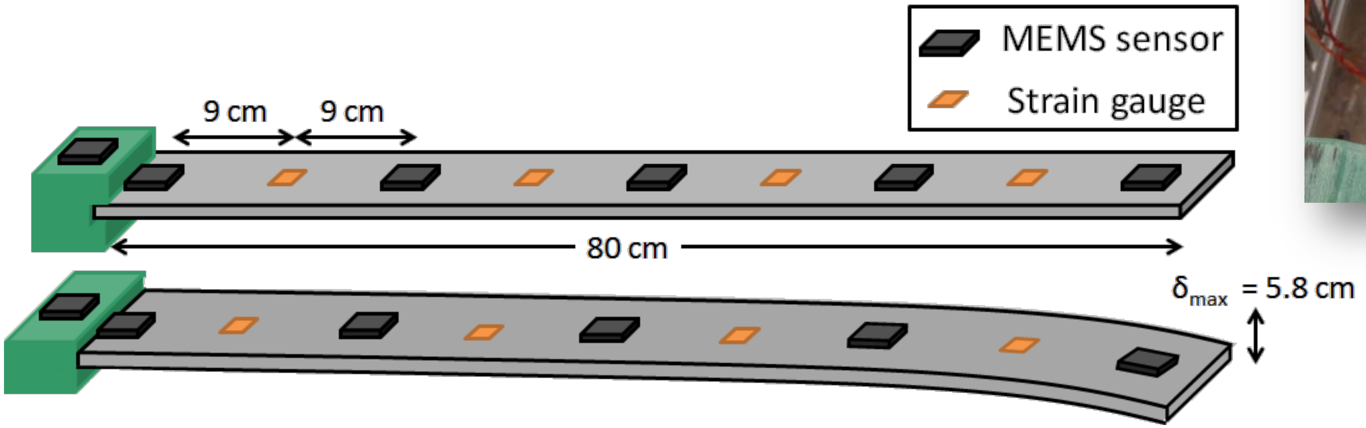
- Detect sensor orientations
- Calculate displacement
- Determine stress and strain distribution throughout a structure

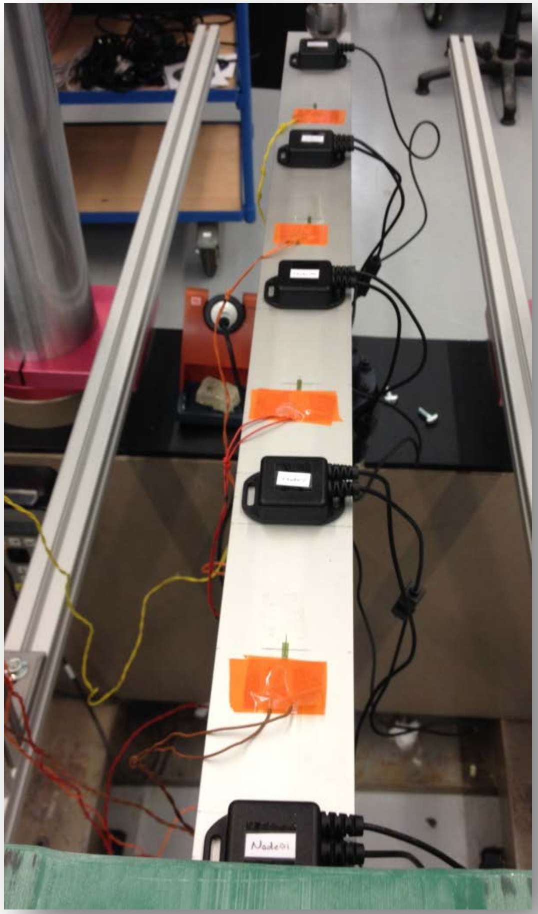
Process flowchart



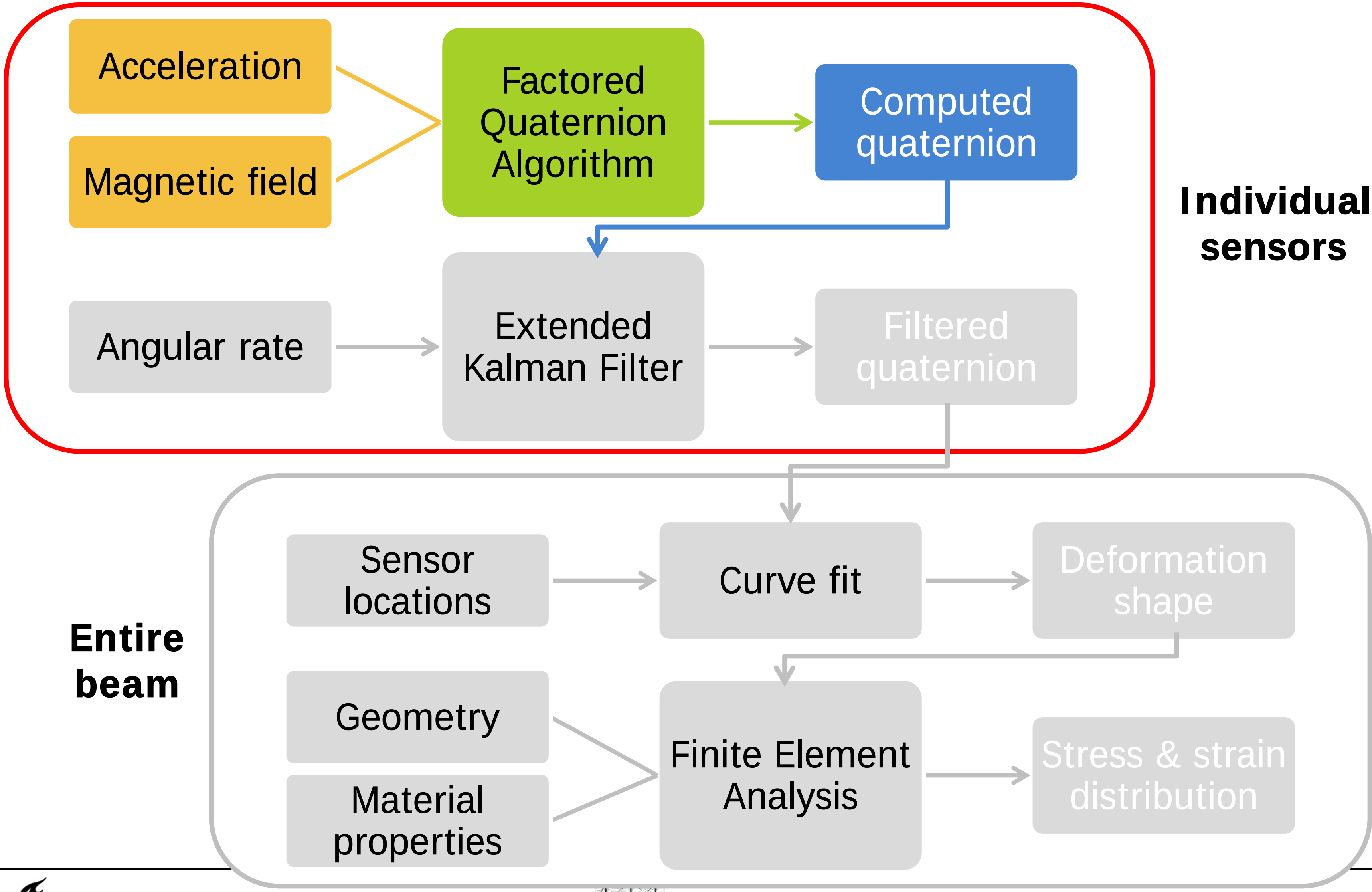
Test setup

- Aluminum cantilever beam with dimensions 80 cm × 6.0 cm × 0.52 cm
- 5 MEMS sensors placed at 18 cm intervals along beam axis
- Reference MEMS sensor at clamp
- Strain gauges located between MEMS
- Stepwise tip displacement: 1.0 cm to 5.8 cm





Process flowchart

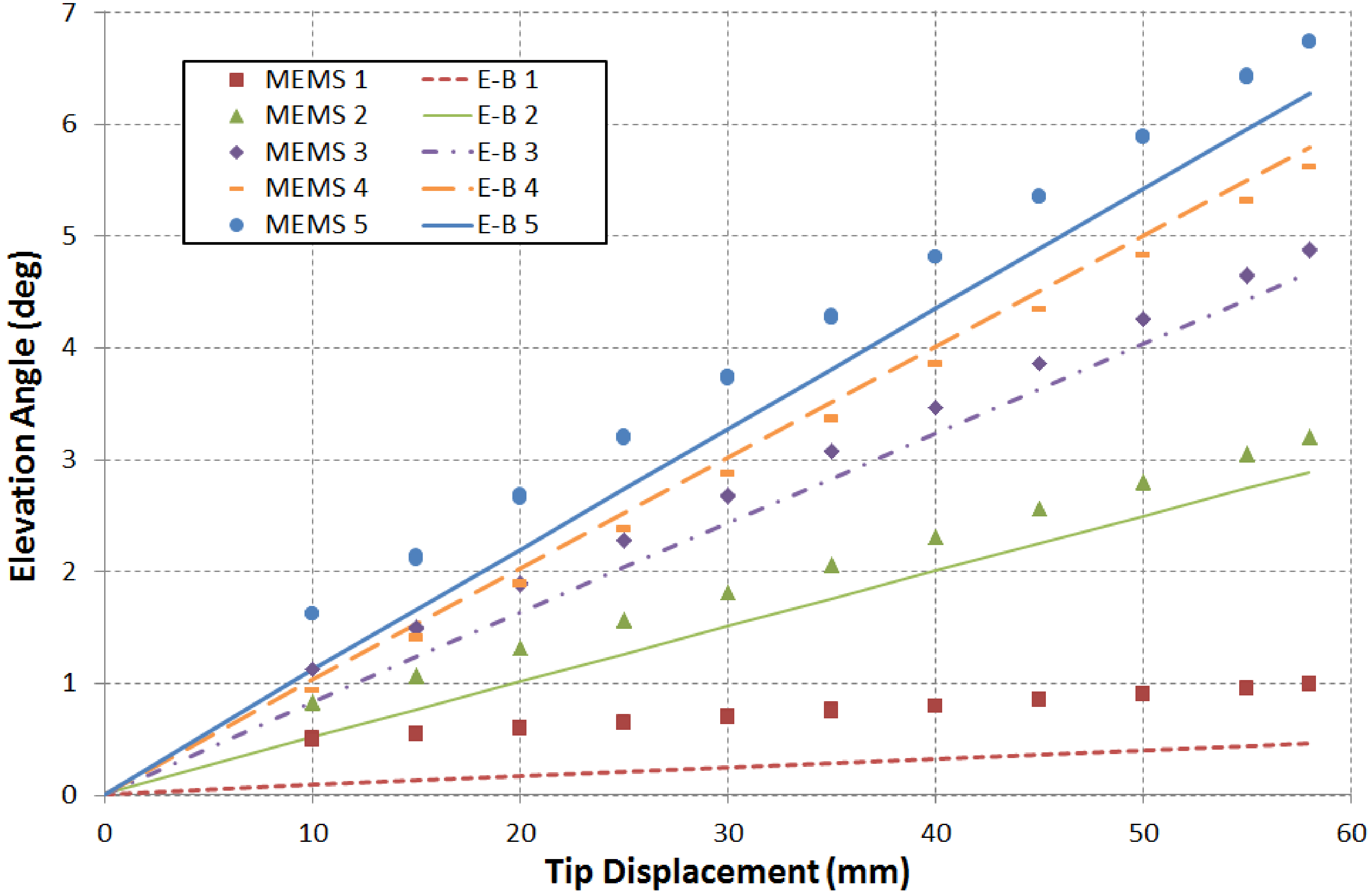


Factored Quaternion Algorithm[1]

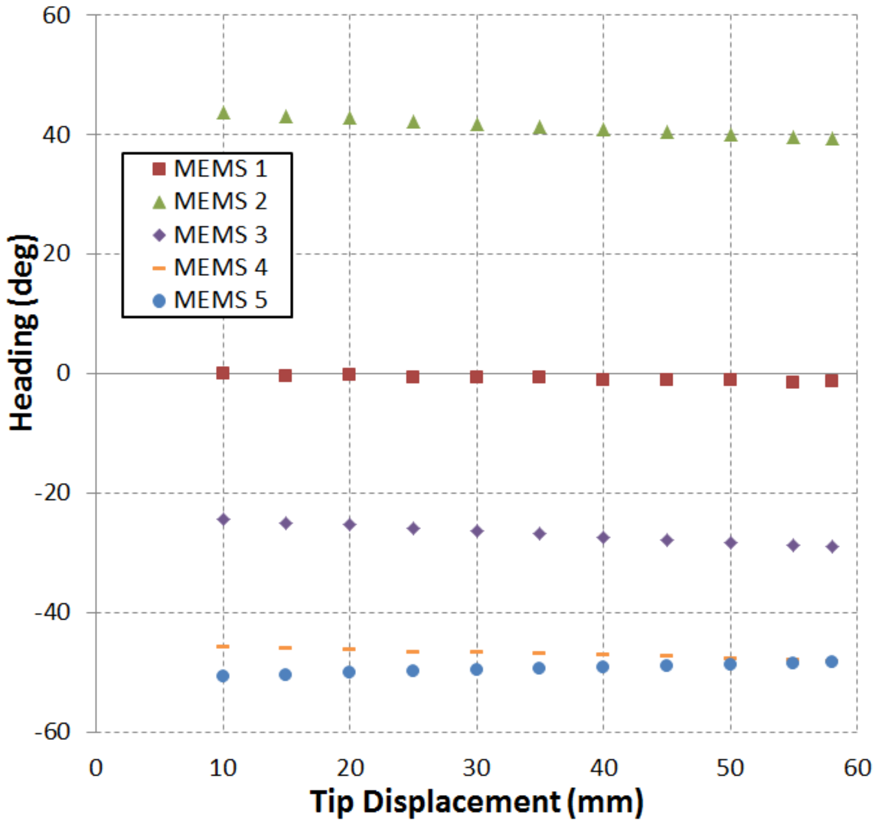
- Elevation and roll angles determined from acceleration measurements
- Gravitational acceleration provides vertical reference
- Magnetic field data used only to determine heading
- Local geomagnetic field strength and orientation obtained from USGS

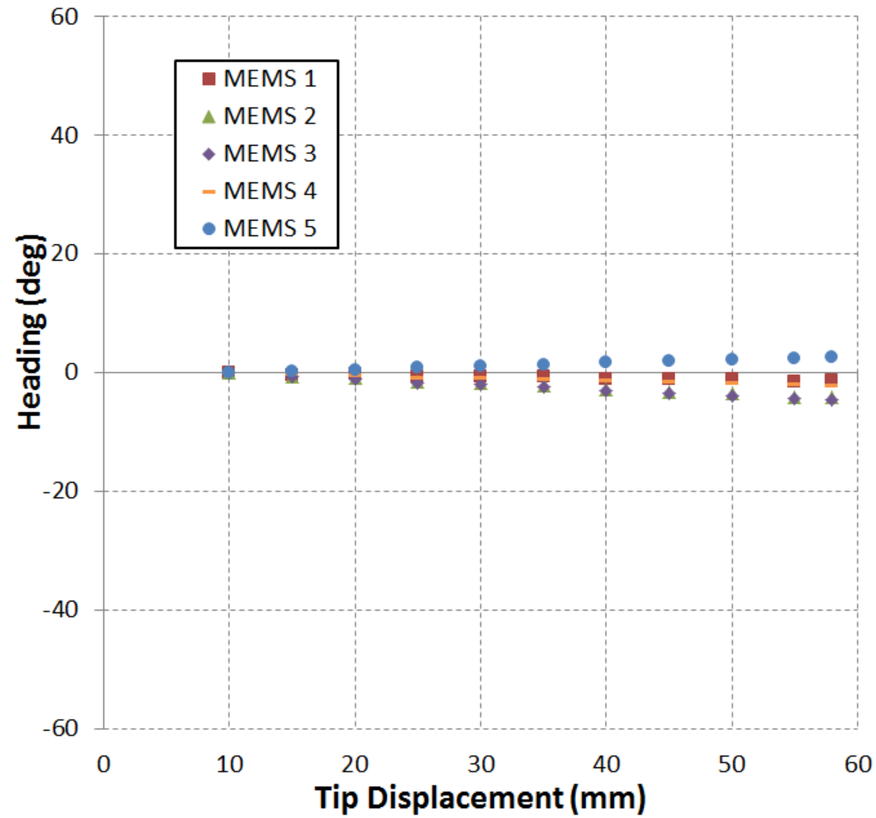
[1] Yun, X., Bachmann, E. R., and McGhee, R. B., "A Simplified Quaternion-Based Algorithm for Orientation Estimation from Earth Gravity and Magnetic Field Measurements," *IEEE Trans Instrum Meas* 57(3), 638–650 (2008).

Angle of elevation

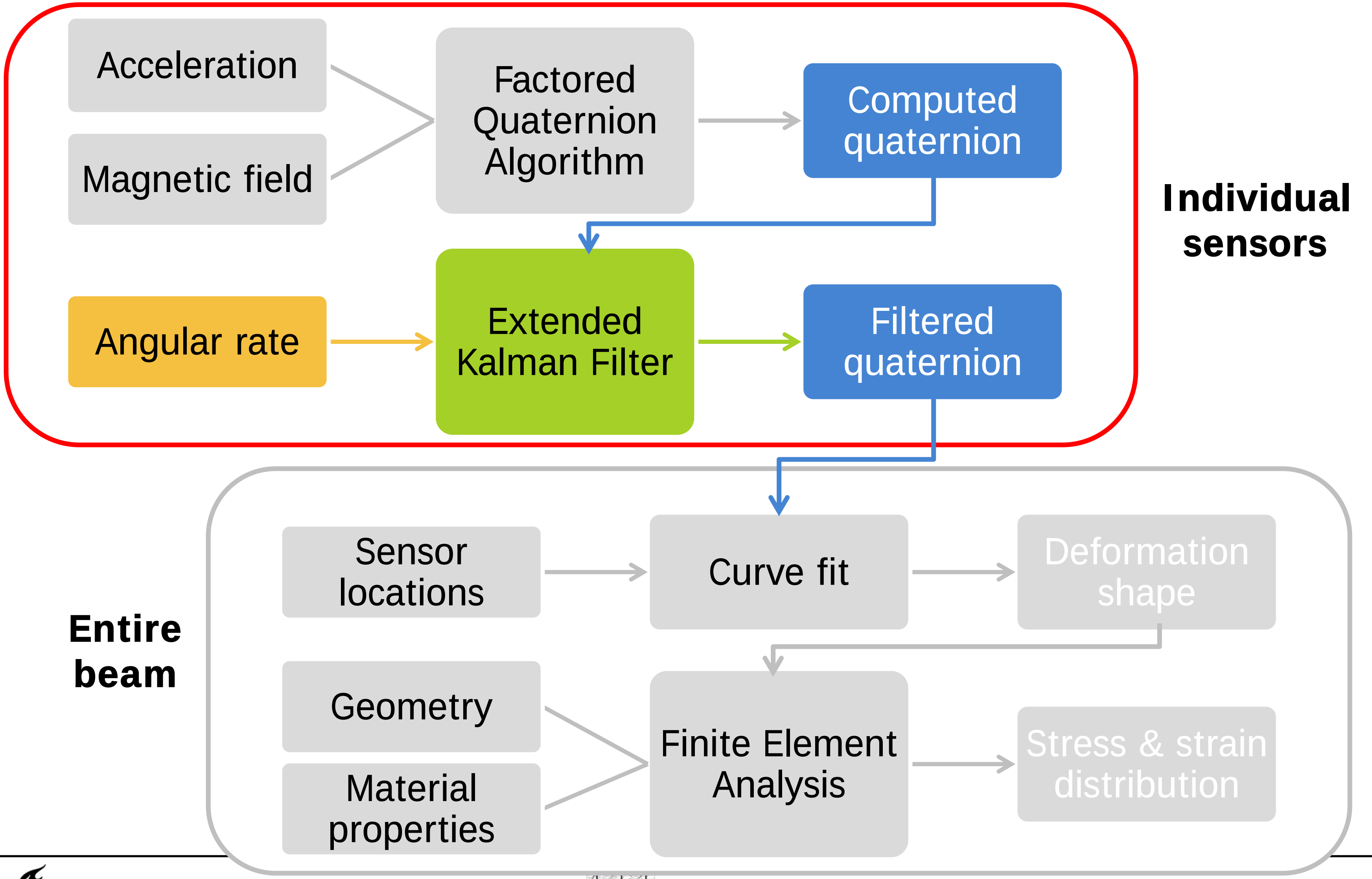


Heading


60
40
20
0
-20
-40
-60
Heading (deg)
0
10
20
30
40
50
60
Tip Displacement (mm)
MEMS 1
MEMS 2
MEMS 3
MEMS 4
MEMS 5


60
40
20
0
-20
-40
-60
Heading (deg)
0
10
20
30
40
50
60
Tip Displacement (mm)
MEMS 1
MEMS 2
MEMS 3
MEMS 4
MEMS 5

Process flowchart



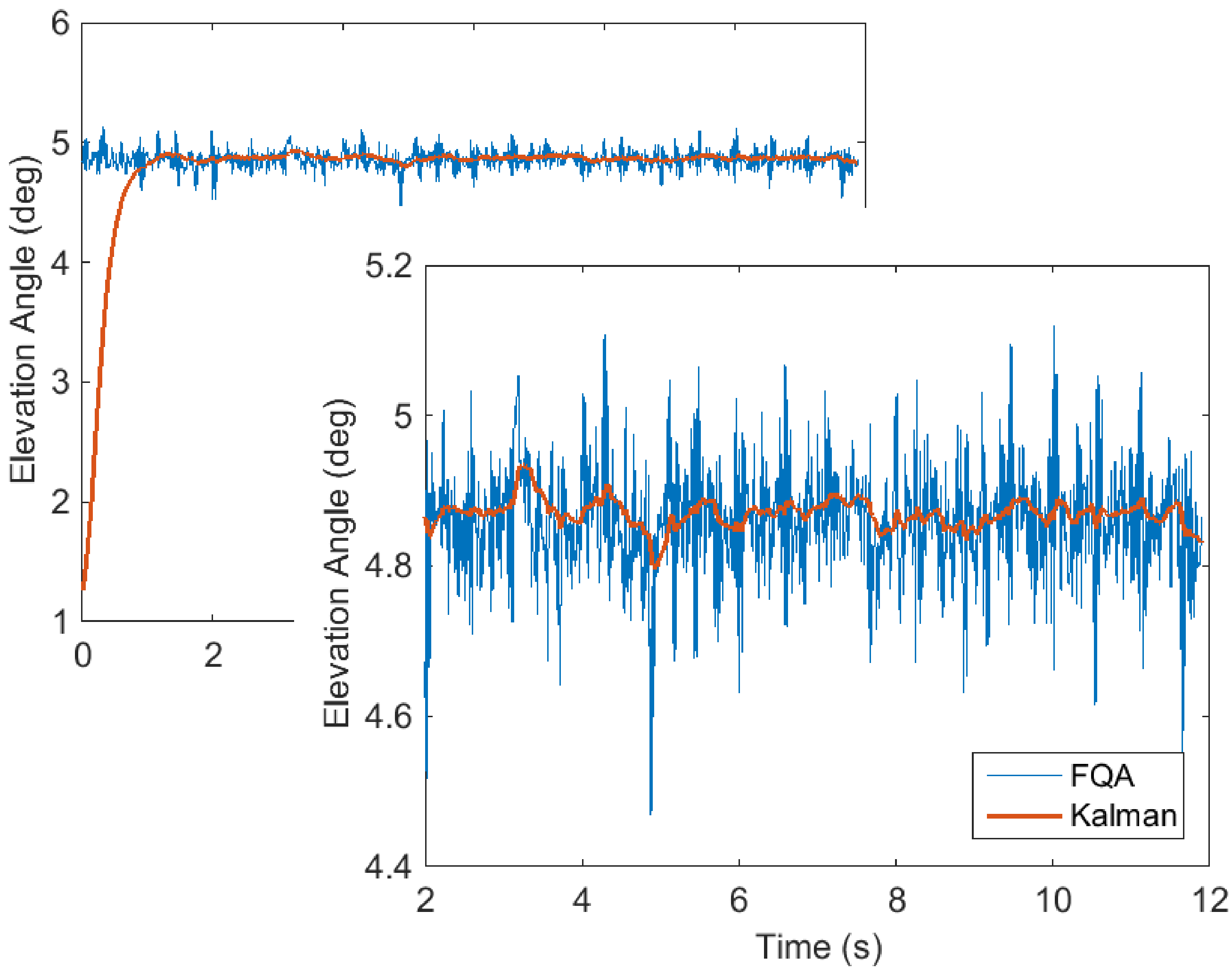
Extended Kalman Filter

- Utilizes calculated quaternion from FQA
- Incorporates angular rate information from gyroscopes
- State vector: $$x = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$ Measurement vector: $$z = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$
- Update equations:

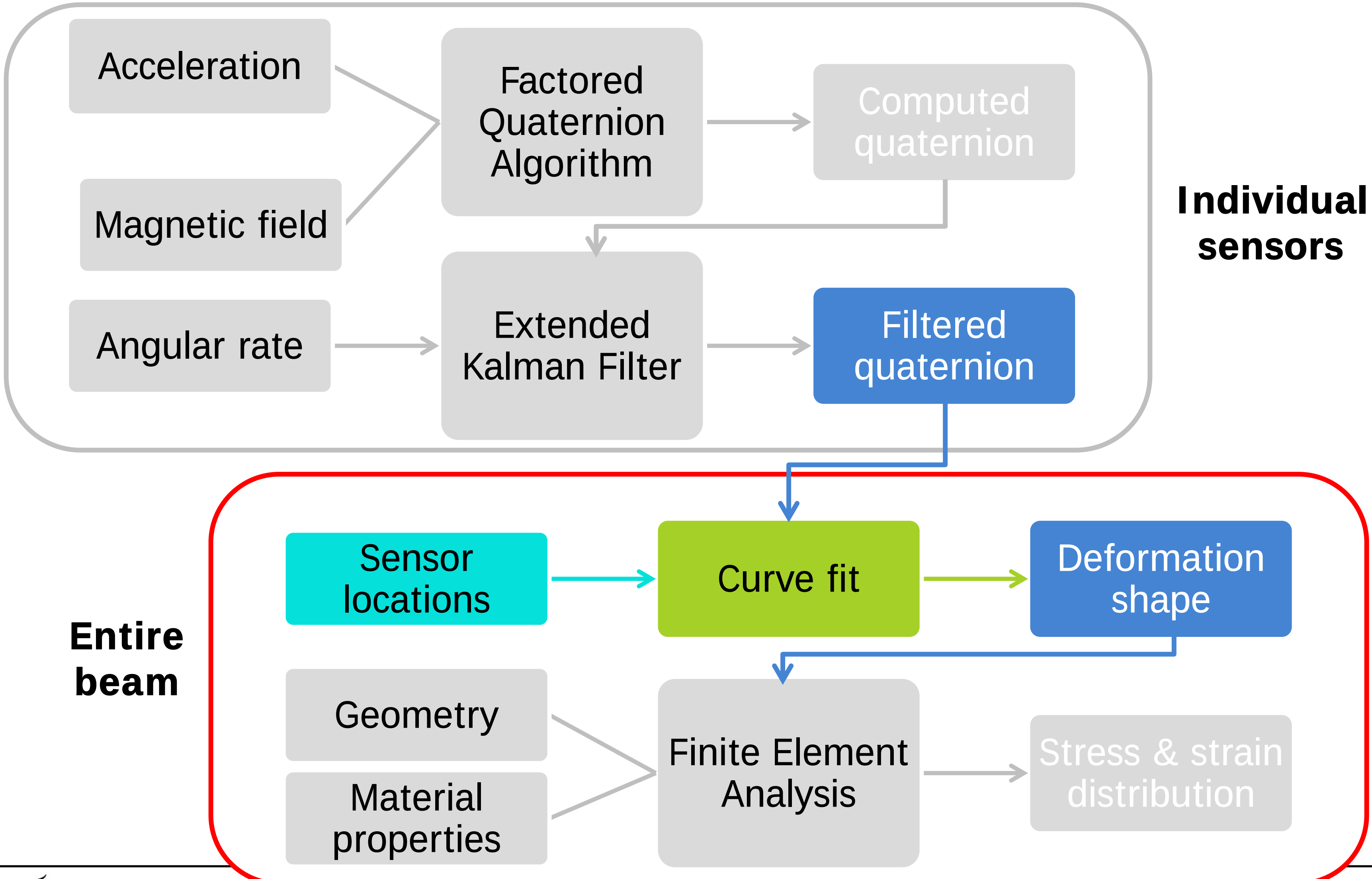
$$\begin{bmatrix} \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\omega}_3 \end{bmatrix} = \frac{1}{\tau}\left(-\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}\right)$$ and $$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \otimes \begin{bmatrix} 0 \\ \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}$$

[2] Yun, X., and Bachmann, E. R., "Design, Implementation, and Experimental Results of a Quaternion-Based Kalman Filter for Human Body Motion Tracking," *IEEE Trans Robotics* 22(6), 1216–1227 (2006).

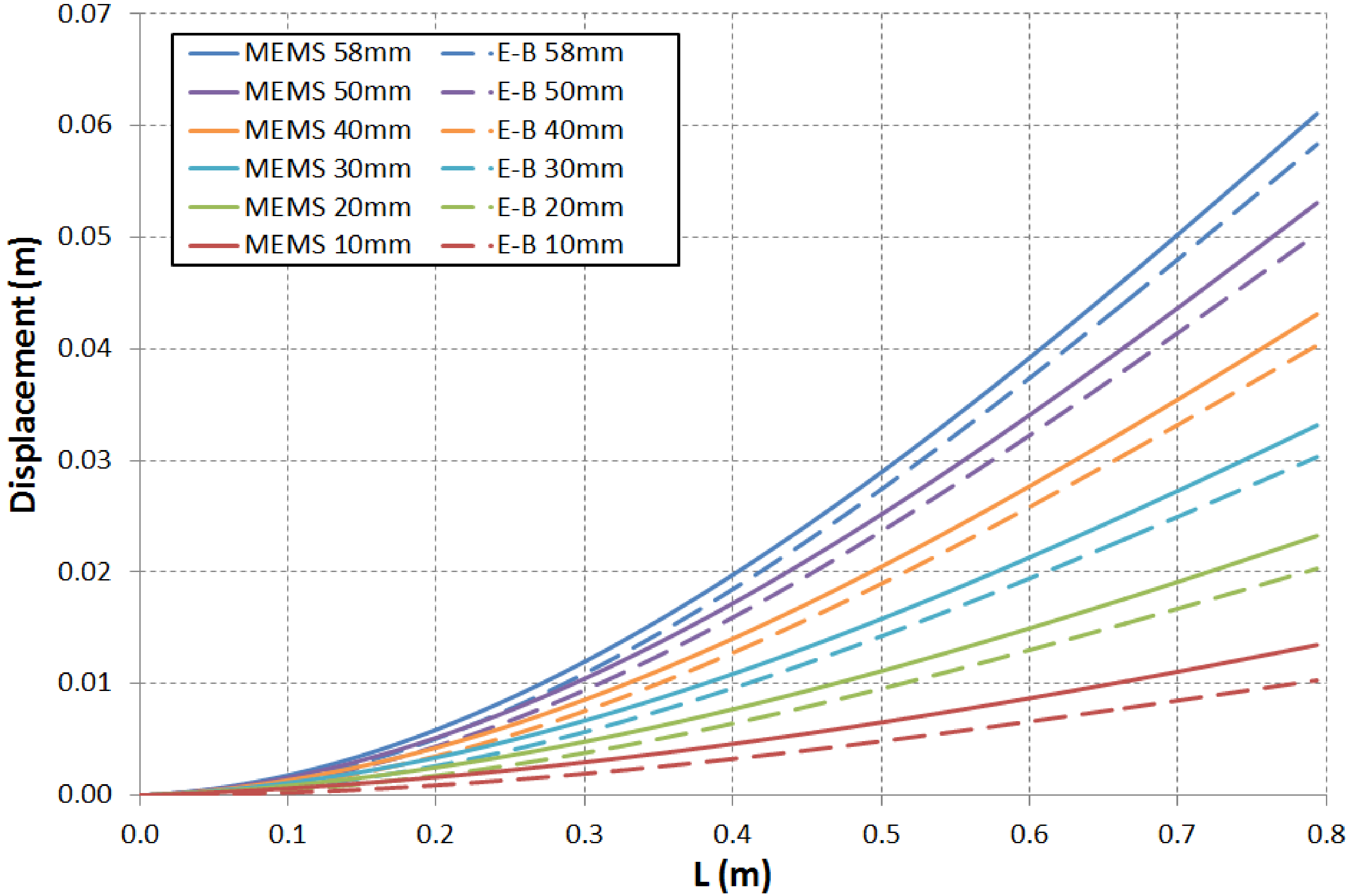
Application of EKF



Process flowchart

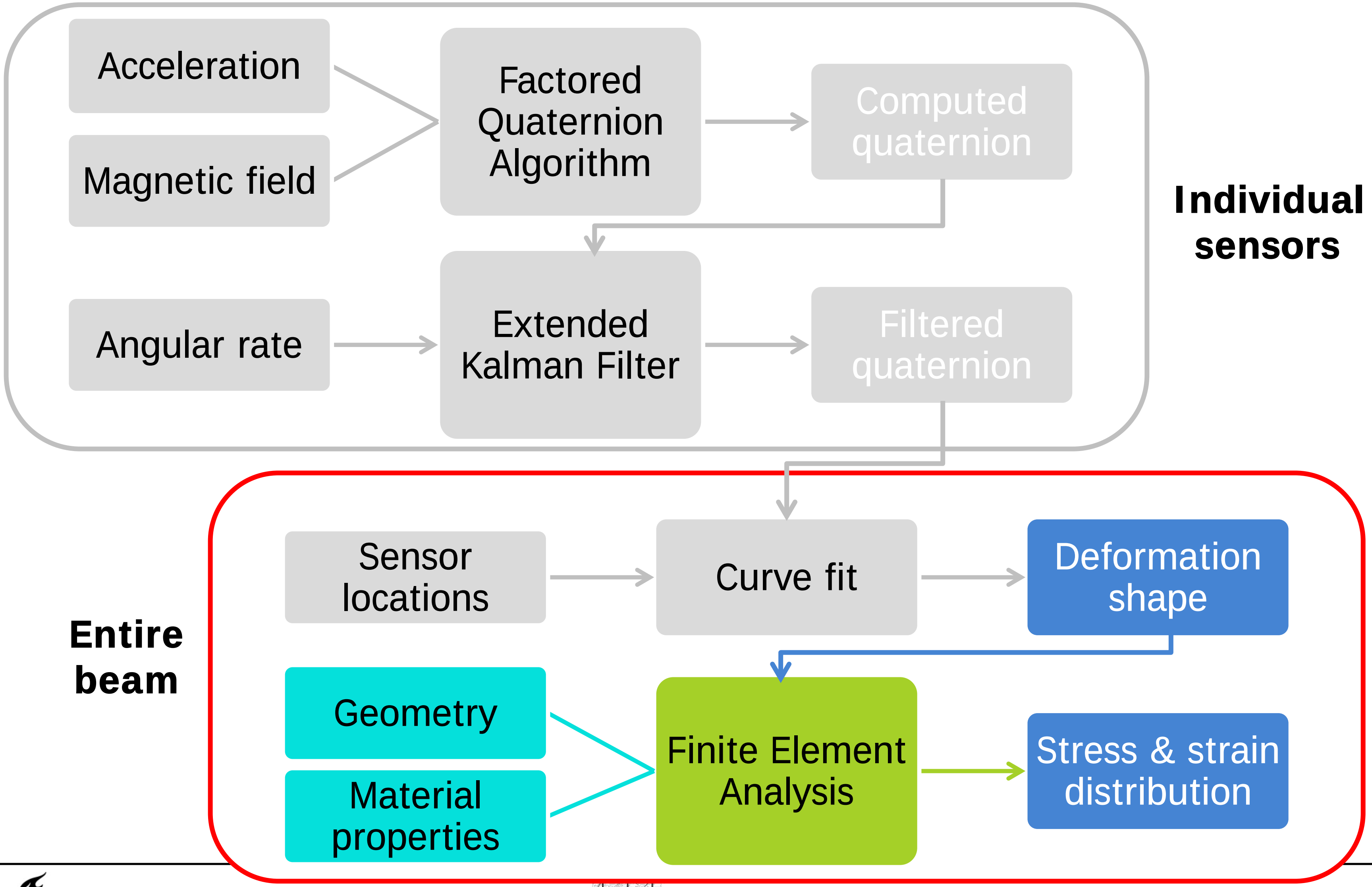


Beam shape

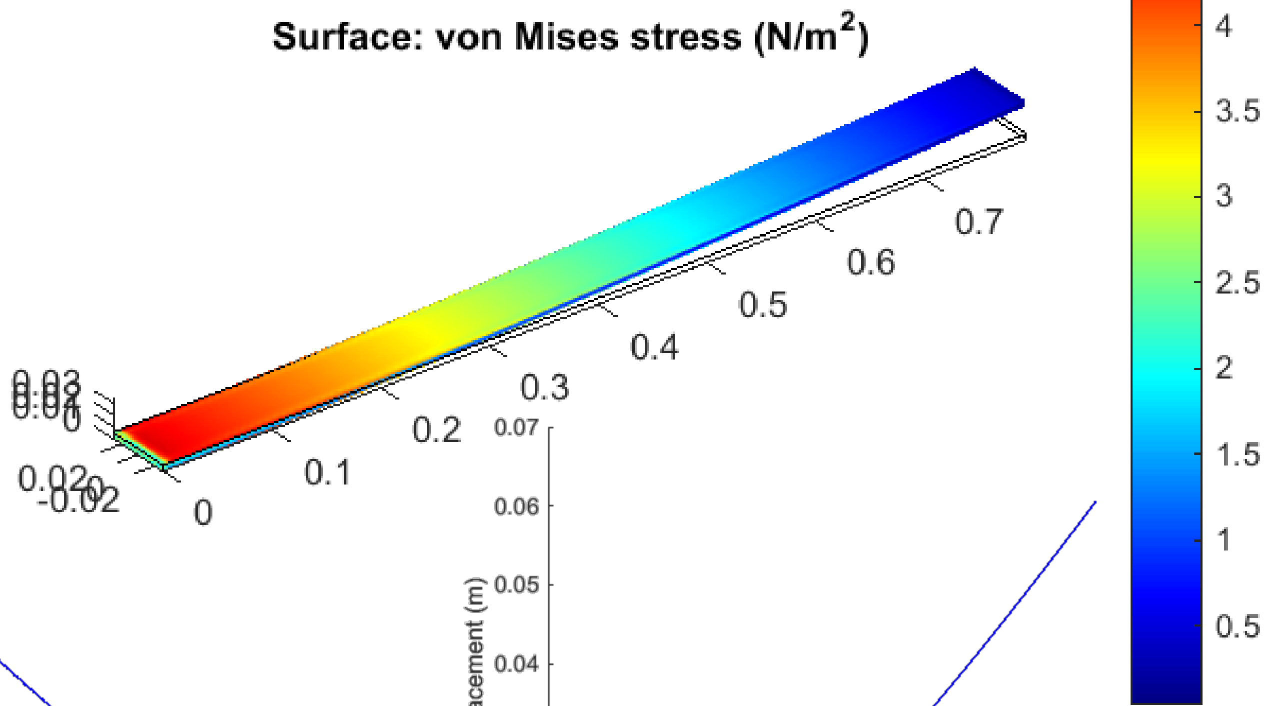


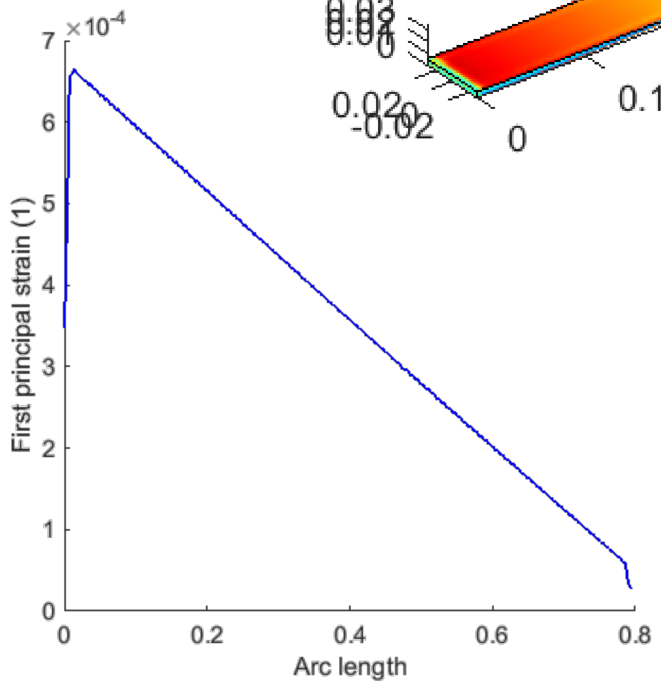
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
MEMS 58mm
MEMS 50mm
MEMS 40mm
MEMS 30mm
MEMS 20mm
MEMS 10mm
E-B 58mm
E-B 50mm
E-B 40mm
E-B 30mm
E-B 20mm
E-B 10mm
Displacement (m)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
L (m)

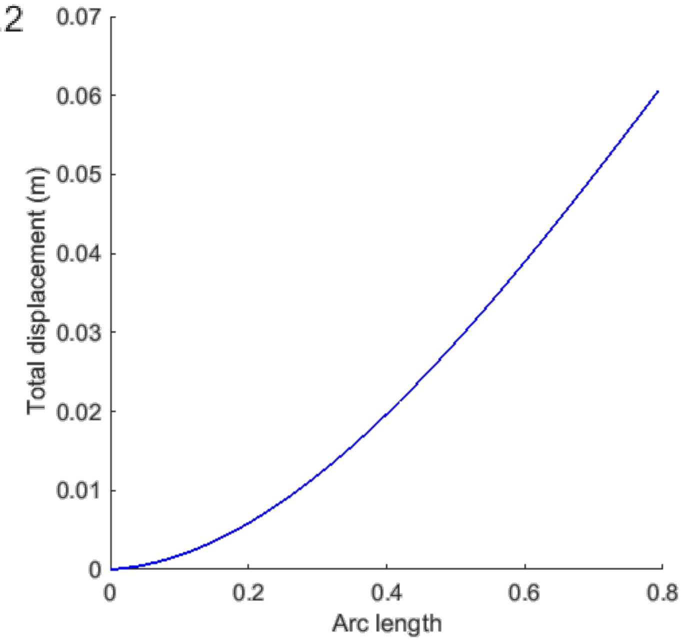
Process flowchart



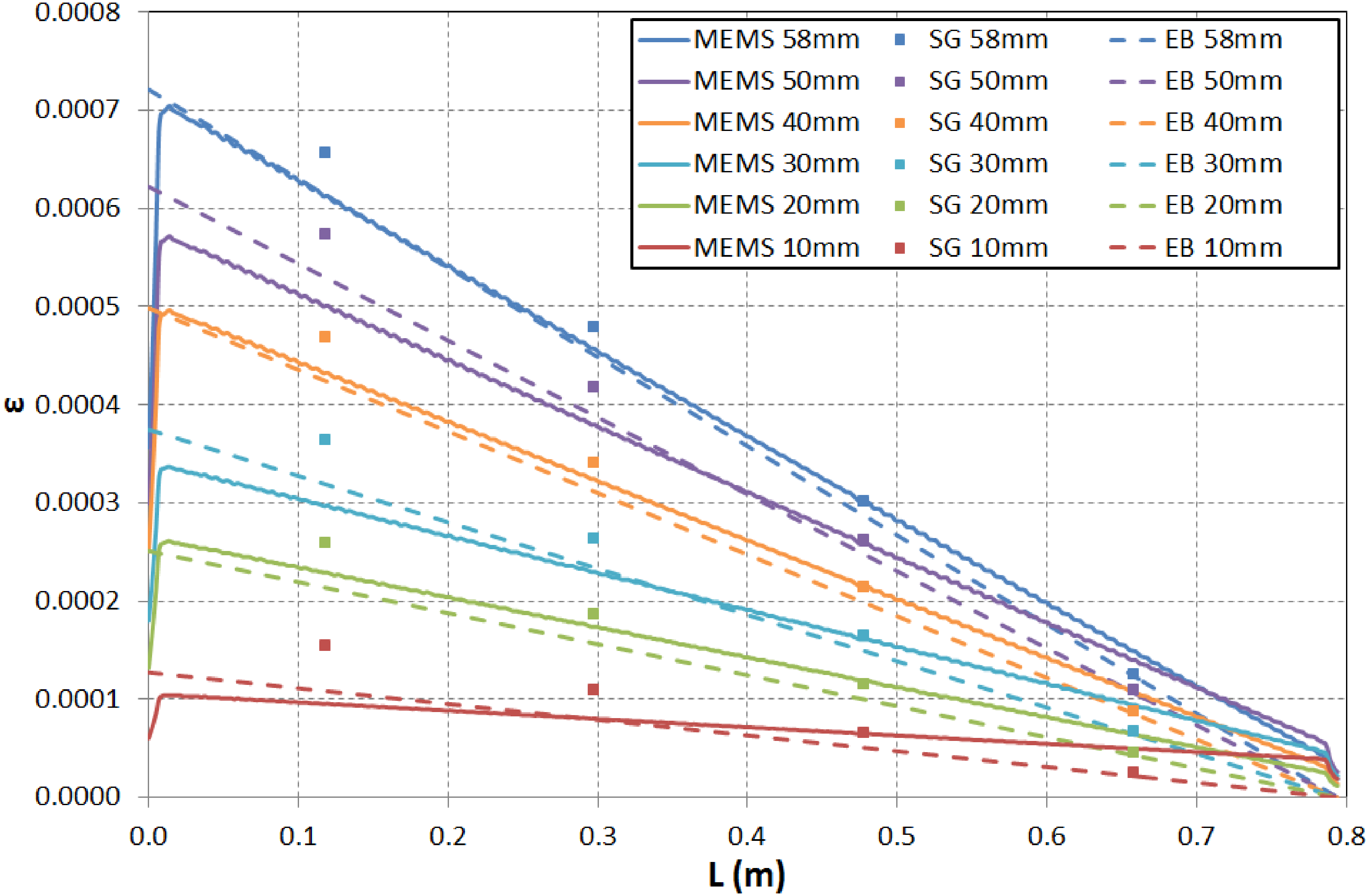
Finite Element Analysis







Strain



0.0008
0.0007
0.0006
0.0005
ω 0.0004
0.0003
0.0002
0.0001
0.0000
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
L (m)
MEMS 58mm
MEMS 50mm
MEMS 40mm
MEMS 30mm
MEMS 20mm
MEMS 10mm
SG 58mm
SG 50mm
SG 40mm
SG 30mm
SG 20mm
SG 10mm
EB 58mm
EB 50mm
EB 40mm
EB 30mm
EB 20mm
EB 10mm

Conclusions and Future Work

- MEMS can be used to detect changes in orientation
- Kalman filtering improves orientation values derived from accelerometer, magnetometer and gyroscope data
- Curve fit to sensor orientations provides displacement for a finite element model of a structure

Future work

- Reduce sensitivity to magnetic interference
- Adapt filtering algorithm for rotating environment