CLAIMS

1. A computer-implemented method for object localisation, comprising executing on one or more processors the steps of:

predicting a state vector x_k of an object at time k using Equation (1):

$$x_k = F_k x_{k-1} \qquad (1)$$

wherein

F_k represents a state-transition matrix, and

x_{k-1} represents the state vector at time $k-1$;

predicting a covariance matrix P_k of the state vector x_k of the object using Equation (2):

$$P_k = F_k P_{k-1} F_k^T + Q_k \qquad (2)$$

wherein

P_{k-1} represents an estimated covariance matrix at time $k-1$,

F_k^T represents a transpose of the state-transition matrix F_k, and

Q_k represents a process noise covariance;

receiving inertial measurement unit (IMU) data comprising IMU accelerometer data and IMU gyroscope data;

receiving ultra-wideband (UWB) data;

determining observation residual y_k using Equation (3):

$$y_k = z_k - H_k x_k \qquad (3)$$

wherein

z_k represents an observation of a true state of the object based on the IMU data and the UWB data, wherein z_k is one of the IMU accelerometer data, the IMU gyroscope data and the UWB data, and

H_k represents a sensor observation matrix;

determining an optimal Kalman gain using Equation (4):

$$K_k = P_k H_k^T (H_k P_k H_k^T + R_k)^{-1} \qquad (4)$$

wherein

H_k^T represents a transpose of the sensor observation matrix H_k, and

R_k represents an observation or sensor noise covariance, wherein the observation or sensor noise covariance R_k is one of an IMU accelerometer sensor noise covariance R_{acc}, an IMU gyroscope sensor noise covariance R_{gyro}, and an UWB sensor or observation noise covariance R_{UWB} corresponding to the respective IMU accelerometer data, IMU gyroscope data and UWB data respectively; and

updating the predicted state vector x_k using Equation (5) to generate a localization solution L_{est}:

$$x_k = x_k + K_k y_k \qquad (5),$$

wherein updating the predicted state vector x_k includes an iterative process associated with each of the IMU accelerometer data, the IMU gyroscope data and the UWB data.

2. The computer-implemented method for object localisation according to claim 1, wherein the state vector x_k is defined by Equation (6):

$$x_k = [p_k, v_k, hd_k, a_k] \qquad (6)$$

wherein

p_k represents a three-dimensional (3D) position of the object at time k,

v_k represents velocity states of the object at time k,

hd_k represents an absolute navigational heading of the object in a single dimension (1D) at time k, and

a_k represents an acceleration of the object at time k.

3. The computer-implemented method for object localisation according to claim 2, wherein a_k represents the acceleration of the object in two dimensions (2D), excluding gravitational acceleration.

4. The computer-implemented method for object localisation according to claim 3, wherein each element of the state vector x_k is modelled by Equations (7) to (12):

$$p_k = p_{k-1} + T_s v_{k-1} \quad (7)$$

$$v_k^x = \left(v_{k-1}^x \cos(hd_{k-1}) + T_s \sqrt{{a_{k-1}^x}^2 + {a_{k-1}^y}^2} \right) \cos(hd_{k-1}) \quad (8)$$

$$v_k^y = \left(v_{k-1}^y \sin(hd_{k-1}) + T_s \sqrt{{a_{k-1}^x}^2 + {a_{k-1}^y}^2} \right) \sin(hd_{k-1}) \quad (9)$$

$$v_k^z = v_{k-1}^z \quad (10)$$

$$hd_k = hd_{k-1} \quad (11)$$

$$a_k = a_{k-1} \quad (12)$$

wherein

p_{k-1} represents the three-dimensional (3D) position of the object at time $k-1$,

v_{k-1} represents the velocity states of the object at time $k-1$,

T_s represents a time step,

v_k^x, v_k^y and v_k^z represent the velocity states of the object at time k in x, y and z dimensions, respectively,

v_{k-1}^x, v_{k-1}^y and v_{k-1}^z represent the velocity states of the object at time $k-1$ in x, y and z dimensions, respectively,

hd_{k-1} represents the absolute navigational heading of the object in 1D at time $k-1$,

a_{k-1} represents the acceleration of the object at time $k-1$, and

a_{k-1}^x and a_{k-1}^y represent navigational accelerations of the object at time $k-1$ in x and y dimensions, respectively,

wherein Equations (7) to (12) form the state transition matrix F_k, and the state vector x_k of the object at time k is predicted using the state transition from the time $k-1$ to the time k.

5. The computer-implemented method for object localisation according to any one of the preceding claims, wherein z_k is one of the IMU accelerometer data $\left[a_n^i[0:1]\right]$, a_n^i representing an instantaneous navigational acceleration of the object in a rigid navigation frame, the IMU gyroscope data $\left[h_n^i[1]\right]$, h_n^i representing an instantaneous navigational heading of the object in the rigid navigation frame, and UWB ranging data $[d_m]$, d_m representing a distance between an m-th anchor and the object computed using a UWB two-way ranging (TWR) protocol.

6. The computer-implemented method for object localisation according to claim 5, wherein the step of determining the observation residual y_k comprises:

calibrating an accelerometer measurement bias b_{a_n} in the rigid navigation frame using Equation (13):

$$b_{a_n} = \frac{1}{N}\sum_{j=1}^{N} C_{bn}(\emptyset^*, \theta^*, \psi^*)a_b^j \qquad (13)$$

wherein

N represents a number of static data points where measurements are stored,

C_{bn} represents a rotation matrix defined by Equation (14) describing orientation of a body frame with respect to the rigid navigation frame:

$$C_{bn} = \begin{bmatrix} \cos(\theta_k)\cos(\psi_k) & \sin(\phi_k)\sin(\theta_k)\cos(\psi_k) - \cos(\phi_k)\sin(\psi_k) & \cos(\phi_k)\sin(\theta_k)\cos(\psi_k) + \sin(\phi_k)\sin(\psi_k) \\ \cos(\theta_k)\sin(\psi_k) & \sin(\phi_k)\sin(\theta_k)\sin(\psi_k) + \cos(\phi_k)\cos(\psi_k) & \cos(\phi_k)\sin(\theta_k)\sin(\psi_k) - \sin(\phi_k)\cos(\psi_k) \\ -\sin(\theta_k) & \sin(\phi_k)\cos(\theta_k) & \cos(\phi_k)\cos(\theta_k) \end{bmatrix} \qquad (14)$$

wherein

θ_k represents a pitch angle of the object,

ψ_k represents a yaw angle of the object, and

$\emptyset_k$ represents a roll angle of the object,

a_b^j represents a three-dimensional (3D) body-frame acceleration for a j^{th} stored data point, and

$\emptyset^*, \theta^*, \psi^*$ represents an optimal roll $\emptyset^*$, pitch θ^* and yaw ψ^* of the object in the rigid navigation frame as defined by Equation (15):

$$\emptyset^*, \theta^*, \psi^* = \min_{-\pi<\emptyset,\theta,\psi<\pi} \sum_{j=1}^{N} C_{bn}(\emptyset, \theta, \psi) a_b^j \qquad (15).$$

7. The computer-implemented method for object localisation according to claim 6, wherein the step of determining the observation residual y_k further comprises:

computing the instantaneous navigational acceleration a_n^i of the object in the rigid navigation frame using Equation (16):

$$a_n^i = C_{bn}(\emptyset^*, \theta^*, \psi^*) a_b^i - b_{a_n} \qquad (16)$$

wherein

a_b^i represents instantaneous 3D body-frame accelerations.

8. The computer-implemented method for object localisation according to claim 6 or 7, wherein the step of determining the observation residual y_k further comprises:

calibrating a gyroscope measurement bias b_{w_n} in the rigid navigation frame using Equation (17)

$$b_{w_n} = \frac{1}{N} \sum_{j=1}^{N} A_{bn}(\emptyset^*, \theta^*, \psi^*) w_b^j \qquad (17)$$

wherein

A_{bn} represents a body to navigation frame matrix for angular velocity as defined by Equation (18):

$$A_{bn} = \begin{bmatrix} 1 & \sin(\phi_k)\tan(\theta_k) & \cos(\phi_k)\tan(\theta_k) \\ 0 & \cos(\phi_k) & -\sin(\phi_k) \\ 0 & \frac{\sin(\phi_k)}{\cos(\theta_k)} & \frac{\cos(\phi_k)}{\cos(\theta_k)} \end{bmatrix} \qquad (18), \text{ and}$$

w_b^j represents a 3D body-frame angular velocity for the j^{th} stored data point.

9. The computer-implemented method for object localisation according to claim 8, wherein the step of determining the observation residual y_k further comprises:

computing an instantaneous navigational angular velocity w_n^i of the object in the rigid navigation frame using Equation (19):

$$w_n^i = \frac{1}{T_s} A_{bn}(\emptyset^*, \theta^*, \psi^*) w_b^i - b_{w_n} \qquad (19)$$

wherein

w_b^i represents instantaneous 3D body-frame angular velocities.

10. The computer-implemented method for object localisation according to claim 9, wherein the step of determining the observation residual y_k further comprises:

computing the instantaneous navigational heading h_n^i of the object in the rigid navigation frame using Equation (20):

$$h_n^i = w_n^i + w_n^{i-1} \qquad (20)$$

wherein

w_n^{i-1} represents a previous instantaneous navigation-frame angular velocity.

11. A non-transitory computer-readable memory storing computer program instructions executable by one or more computer processors to perform operations for object localisation, the operations comprising:

predicting a state vector x_k of an object at time k using Equation (1):

$$x_k = F_k x_{k-1} \qquad (1)$$

wherein

F_k represents a state-transition matrix, and

x_{k-1} represents the state vector at time $k-1$;

predicting a covariance matrix P_k of the state vector x_k of the object using Equation (2):

$$P_k = F_k P_{k-1} F_k^T + Q_k \qquad (2)$$

wherein

P_{k-1} represents an estimated covariance matrix at time $k-1$,

F_k^T represents a transpose of the state-transition matrix F_k, and

Q_k represents a process noise covariance;

receiving inertial measurement unit (IMU) data comprising IMU accelerometer data and IMU gyroscope data;

receiving ultra-wideband (UWB) data;

determining observation residual y_k using Equation (3):

$$y_k = z_k - H_k x_k \qquad (3)$$

wherein

z_k represents an observation of a true state of the object based on the IMU data and the UWB data, wherein z_k is one of the IMU accelerometer data, the IMU gyroscope data and the UWB data, andH_k represents an observation model;

determining an optimal Kalman gain using Equation (4):

$$K_k = P_k H_k^T (H_k P_k H_k^T + R_k)^{-1} \qquad (4)$$

wherein

H_k^T represents a transpose of the sensor observation matrix H_k, and

R_k represents an observation or sensor noise covariance, wherein the observation or sensor noise covariance R_k is one of an IMU accelerometer sensor noise covariance R_{acc}, an IMU gyroscope sensor noise covariance R_{gyro}, and an UWB sensor or observation noise covariance R_{UWB} corresponding to the respective IMU accelerometer data, IMU gyroscope data and UWB data respectively; and

updating the predicted state vector x_k using Equation (5) to generate a localization solution L_{est}:

$$x_k = x_k + K_k y_k \qquad (5),$$

wherein updating the predicted state vector x_k includes an iterative process associated with each of the IMU accelerometer data, the IMU gyroscope data and the UWB data.

12. The non-transitory computer-readable memory according to claim 11, wherein the state vector x_k is defined by Equation (6):

$$x_k = [p_k, v_k, hd_k, a_k] \quad (6)$$

wherein

p_k represents a three-dimensional (3D) position of the object at time k,

v_k represents velocity states of the object at time k,

hd_k represents an absolute navigational heading of the object in a single dimension (1D) at time k, and

a_k represents an acceleration of the object at time k.

13. The non-transitory computer-readable memory according to claim 12, wherein a_k represents the acceleration of the object in two dimensions (2D), excluding gravitational acceleration.

14. The non-transitory computer-readable memory according to claim 12 or 13, wherein each element of the state vector x_k is modelled by Equations (7) to (12):

$$p_k = p_{k-1} + T_s v_{k-1} \quad (7)$$

$$v_k^x = \left(v_{k-1}^x \cos(hd_{k-1}) + T_s \sqrt{{a_{k-1}^x}^2 + {a_{k-1}^y}^2} \right) \cos(hd_{k-1}) \quad (8)$$

$$v_k^y = \left(v_{k-1}^y \sin(hd_{k-1}) + T_s \sqrt{{a_{k-1}^x}^2 + {a_{k-1}^y}^2} \right) \sin(hd_{k-1}) \quad (9)$$

$$v_k^z = v_{k-1}^z \quad (10)$$

$$hd_k = hd_{k-1} \quad (11)$$

$$a_k = a_{k-1} \quad (12)$$

wherein

p_{k-1} represents the three-dimensional (3D) position of the object at time $k-1$,

v_{k-1} represents the velocity states of the object at time $k-1$,

T_s represents a time step,

v_k^x, v_k^y and v_k^z represent the velocity states of the object at time k in x, y and z dimensions, respectively,

v_{k-1}^x, v_{k-1}^y and v_{k-1}^z represent the velocity states of the object at time $k-1$ in x, y and z dimensions, respectively,

hd_{k-1} represents the absolute navigational heading of the object in 1D at time $k-1$,

a_{k-1} represents the acceleration of the object at time $k-1$, and

a_{k-1}^x and a_{k-1}^y represent navigational accelerations of the object at time $k-1$ in x and y dimensions, respectively,

wherein Equations (7) to (12) form the state transition matrix F_k, and the state vector x_k of the object at time k is predicted using the state transition from the time $k-1$ to the time k.

15. The non-transitory computer-readable memory according to any one of claims 11 to 14, wherein z_k is one of the IMU accelerometer data $\left[a_n^i[0:1]\right]$, a_n^i representing an instantaneous navigational acceleration of the object in a rigid navigation frame, the IMU gyroscope data $\left[h_n^i[1]\right]$, h_n^i representing an instantaneous navigational heading of the object in the rigid navigation frame, and UWB ranging data $[d_m]$, d_m representing a distance between an m-th anchor and the object computed using a UWB two-way ranging (TWR) protocol.

16. The non-transitory computer-readable memory according to claim 15, wherein the operation of determining the observation residual y_k comprises:

calibrating an accelerometer measurement bias b_{a_n} in the rigid navigation frame using Equation (13):

$$b_{a_n} = \frac{1}{N}\sum_{j=1}^{N} C_{bn}(\emptyset^*, \theta^*, \psi^*)a_b^j \qquad (13)$$

wherein

N represents a number of static data points where measurements are stored,

C_{bn} represents a rotation matrix defined by Equation (14) describing orientation of a body frame with respect to the rigid navigation frame:

$$C_{bn} = \begin{bmatrix} \cos(\theta_k)\cos(\psi_k) & \sin(\phi_k)\sin(\theta_k)\cos(\psi_k) - \cos(\phi_k)\sin(\psi_k) & \cos(\phi_k)\sin(\theta_k)\cos(\psi_k) + \sin(\phi_k)\sin(\psi_k) \\ \cos(\theta_k)\sin(\psi_k) & \sin(\phi_k)\sin(\theta_k)\sin(\psi_k) + \cos(\phi_k)\cos(\psi_k) & \cos(\phi_k)\sin(\theta_k)\sin(\psi_k) - \sin(\phi_k)\cos(\psi_k) \\ -\sin(\theta_k) & \sin(\phi_k)\cos(\theta_k) & \cos(\phi_k)\cos(\theta_k) \end{bmatrix} \qquad (14)$$

wherein

θ_k represents a pitch angle of the object,

ψ_k represents a yaw angle of the object, and

$\emptyset_k$ represents a roll angle of the object,

a_b^j represents a three-dimensional (3D) body-frame acceleration for a j^{th} stored data point, and

$\emptyset^*, \theta^*, \psi^*$ represents an optimal roll $\emptyset^*$, pitch θ^* and yaw ψ^* of the object in the rigid navigation frame as defined by Equation (15):

$$\emptyset^*, \theta^*, \psi^* = \min_{-\pi<\emptyset,\theta,\psi<\pi} \sum_{j=1}^{N} C_{bn}(\emptyset, \theta, \psi)a_b^j \qquad (15).$$

17. The non-transitory computer-readable memory according to claim 16, wherein the operation of determining the observation residual y_k further comprises:

computing the instantaneous navigational acceleration a_n^i of the object in the rigid navigation frame using Equation (16):

$$a_n^i = C_{bn}(\emptyset^*, \theta^*, \psi^*)a_b^i - b_{a_n} \qquad (16)$$

wherein

a_b^i represents instantaneous 3D body-frame accelerations.

18. The non-transitory computer-readable memory according to claim 16 or 17, wherein the operation of determining the observation residual y_k further comprises:

calibrating a gyroscope measurement bias b_{w_n} in the rigid navigation frame using Equation (17)

$$b_{w_n} = \frac{1}{N}\sum_{j=1}^{N} A_{bn}(\emptyset^*, \theta^*, \psi^*) w_b^j \qquad (17)$$

wherein

A_{bn} represents a body to navigation frame matrix for angular velocity as defined by Equation (18):

$$A_{bn} = \begin{bmatrix} 1 & \sin(\phi_k)\tan(\theta_k) & \cos(\phi_k)\tan(\theta_k) \\ 0 & \cos(\phi_k) & -\sin(\phi_k) \\ 0 & \frac{\sin(\phi_k)}{\cos(\theta_k)} & \frac{\cos(\phi_k)}{\cos(\theta_k)} \end{bmatrix} \qquad (18), \text{ and}$$

w_b^j represents a 3D body-frame angular velocity for the j^{th} stored data point.

19. The non-transitory computer-readable memory according to claim 18, wherein the operation of determining the observation residual y_k further comprises:

computing an instantaneous navigational angular velocity w_n^i of the object in the rigid navigation frame using Equation (19):

$$w_n^i = \frac{1}{T_s} A_{bn}(\emptyset^*, \theta^*, \psi^*) w_b^i - b_{w_n} \qquad (19)$$

wherein

w_b^i represents instantaneous 3D body-frame angular velocities.

20. The non-transitory computer-readable memory according to claim 19, wherein the operation of determining the observation residual y_k further comprises:

computing the instantaneous navigational heading h_n^i of the object in the rigid navigation frame using Equation (20):

$$h_n^i = w_n^i + w_n^{i-1} \qquad (20)$$

wherein

w_n^{i-1} represents a previous instantaneous navigation-frame angular velocity.

5