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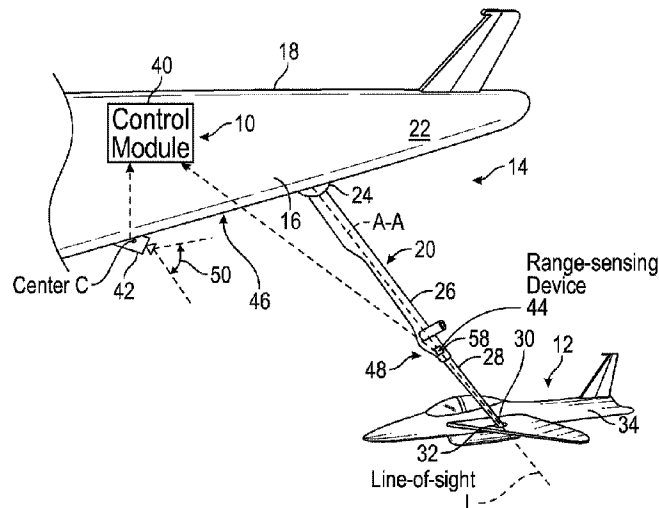
(71) Demandeur/Applicant:
THE BOEING COMPANY, US

(72) Inventeurs/Inventors:
LEACH, WILLIAM K., US;
NGUYEN, LEON, US;
HUNG, FAN HIN, US;
CHEN, YANG, US;
KHOSLA, DEEPAK, US;
SMITH, HADEN H., US

(74) Agent: SMART & BIGGAR LLP

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(54) Title: SYSTEM FOR REFINING A SIX DEGREES OF FREEDOM POSE ESTIMATE OF A TARGET OBJECT



(57) **Abrégé/Abstract:**

A system for refining a six degrees of freedom pose estimate of a target object based on a one-dimensional measurement includes a camera and a range-sensing device. The range-sensing device is configured to determine an actual distance measured between the range-sensing device and an actual point of intersection. The range-sensing device projects a line-of-sight that intersects with the target object at the actual point of intersection. The system also includes one or more processors in electronic communication with the camera and the range-sensing device and a memory coupled to the processors. The memory stores data into one or more databases and program code that, when executed by the processors, causes the system to predict the six degrees of freedom pose estimate of the target object. The system also determines a revised six degrees of freedom pose estimate of the target object based on at least an absolute error.

ABSTRACT

A system for refining a six degrees of freedom pose estimate of a target object based on a one-dimensional measurement includes a camera and a range-sensing device.

5 The range-sensing device is configured to determine an actual distance measured between the range-sensing device and an actual point of intersection. The range-sensing device projects a line-of-sight that intersects with the target object at the actual point of intersection. The system also includes one or more processors in electronic communication with the camera and the range-sensing device and a memory coupled
10 to the processors. The memory stores data into one or more databases and program code that, when executed by the processors, causes the system to predict the six degrees of freedom pose estimate of the target object. The system also determines a revised six degrees of freedom pose estimate of the target object based on at least an absolute error.

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SYSTEM FOR REFINING A SIX DEGREES OF FREEDOM POSE ESTIMATE OF A TARGET OBJECT

BACKGROUND

5 The present disclosure relates to a system and method of refining a six degrees of freedom pose estimate of a target object. More particularly, the present disclosure is directed towards a system and method of refining a six degrees of freedom pose estimate of the target object based on a single one-dimensional measurement.

10 Six degrees of freedom (6DOF) refers to the freedom of movement of a rigid body in three-dimensional space. Specifically, the rigid body may move in three dimensions, on the x, y, and z axes, as well as change orientation between the three axes through rotation, which are referred to as pitch, roll, and yaw.

15 Image-based pose estimation systems may estimate a six degrees of freedom pose of an object. Furthermore, many image-based pose estimation systems also utilize some type of refinement process for revising an initial six degrees of freedom pose estimate. Some types of pose estimate refinement processes utilize a three-dimension depth map or, in the alternative, numerous two-dimension distance measurements where a laser range finder is used to take the two-dimensional distance measurements. However, both the three-dimensional depth map and the two-dimensional distance measurements
20 typically require significant processing and memory allocation requirements. Moreover, the laser range finder used in the two-dimensional distance measurement approach may require precisely manufactured moving parts in order to maintain consistent two-dimensional distance measurements, which in turn adds cost to the system. Additionally, some types of pose estimate refinement approaches may require
25 specialized calibration patterns or correspondence markers for registering the scan lines of the laser range finder with corresponding features that are part of a model.

SUMMARY

According to several aspects, a system for refining a six degrees of freedom pose estimate of a target object based on a one-dimensional measurement is disclosed. The system includes a camera configured to capture image data of the target object and a range-sensing device configured to determine an actual distance measured between the range-sensing device and an actual point of intersection. The range-sensing device projects a line-of-sight that intersects with the target object at the actual point of intersection. The system also includes one or more processors in electronic communication with the camera and the range-sensing device as well as a memory coupled to the one or more processors. The memory stores data into one or more databases and program code that, when executed by the one or more processors, causes the system to predict, based on the image data of the target object, the six degrees of freedom pose estimate of the target object. The system determines an estimated point of intersection representing where the line-of-sight intersects with the six degrees of freedom pose estimate of the target object. The system also determines an estimated distance measured between the range-sensing device and the estimated point of intersection. The system calculates an absolute error associated with the six degrees of freedom pose estimate of the target object based on a difference between the actual distance and the estimated distance. The system then determines a revised six degrees of freedom pose estimate of the target object based on at least the absolute error.

In another aspect, an aerial refueling system for a supply aircraft is disclosed. The aerial refueling system includes a boom assembly including a nozzle and a system for determining a revised six degrees of freedom pose estimate of a fuel receptacle located on a receiver aircraft. The nozzle of the boom assembly is configured to engage with a fuel receptacle of the receiver aircraft during a refueling operation. The system includes a camera configured to capture image data of the receiver aircraft and the fuel receptacle and a range-sensing device configured to determine an actual distance measured between the range-sensing device and an actual point of intersection. The

range-sensing device projects a line-of-sight that intersects with the receiver aircraft at the actual point of intersection. The system also includes one or more processors in electronic communication with the camera and the range-sensing device and a memory coupled to the one or more processors. The memory stores data into one or more databases and program code that, when executed by the one or more processors, causes the system to predict, based on the image data of the fuel receptacle located on a receiver aircraft, the six degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft. The system determines an estimated point of intersection representing where the line-of-sight intersects with the six degrees of freedom pose estimate of the receiver aircraft. The system determines an estimated distance measured between the range-sensing device and the estimated point of intersection. The system calculates an absolute error associated with the six degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft based on a difference between the actual distance and the estimated distance. The system then determines a revised six degrees of freedom pose estimate based on at least the absolute error.

In yet another aspect, a method for refining a six degrees of freedom pose estimate of a target object is disclosed. The method includes capturing, by a camera, image data of the target object. The method also includes determining, by a range-sensing device, an actual distance measured between the range-sensing device and an actual point of intersection, where the range-sensing device projects a line-of-sight that intersects with the target object at the actual point of intersection. The method also includes predicting, based on the image data of the target object, the six degrees of freedom pose estimate of the target object. The method further includes determining an estimated point of intersection representing where the line-of-sight intersects with the six degrees of freedom pose estimate of the target object. The method further includes determining an estimated distance measured between the range-sensing device and the estimated point of intersection. The method also includes calculating an absolute error associated with the six degrees of freedom pose estimate of the target object based on a difference between the actual distance and the estimated distance. Finally, the method includes

determining a revised six degree of freedom pose estimate based on at least the absolute error.

The features, functions, and advantages that have been discussed may be achieved independently in various embodiments or may be combined in other embodiments
5 further details of which can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings described herein are for illustration purposes only and are not intended to limit the scope of the present disclosure in any way.

10 FIG. 1 is an illustration of the disclosed system for refining a six degrees of freedom pose estimate of a target object, where the system is located upon a supply aircraft and the target object is a fuel receptacle of a receiver aircraft, according to an exemplary embodiment;

15 FIG. 2 is a diagram illustrating an extending arm, the receiver aircraft, and the six degrees of freedom pose estimate of the supply aircraft, according to an exemplary embodiment;

20 FIG. 3 is an illustration of an exemplary approach for determining the six degrees of freedom pose estimate of a target object based on a plurality of two-dimensional keypoints and a plurality of three-dimensional keypoints, according to an exemplary embodiment;

FIGS. 4A-4B are a process flow diagram illustrating a method for refining a six degrees of freedom pose estimate of the target object, according to an exemplary embodiment;

25 FIG. 4C is a process flow diagram illustrating a method for determining the reprojection error; and

FIG. 5 is an illustration of a computer system for the disclosed system shown in FIG. 1, according to an exemplary embodiment.

DETAILED DESCRIPTION

The present disclosure relates to a system and method of refining a six degrees of freedom pose estimate of a target object based on a single one-dimensional measurement. The system includes a control module in electronic communication with a camera and a range-sensing device. The camera is configured to capture image data of the target object, and the range-sensing device is configured to determine the one-dimensional measurement. The range-sensing device determines an actual distance measured between the range-sensing device and an actual point of intersection W' . Specifically, the actual point of intersection W' represents where a line-of-sight projected by the range-sensing device intersects with the target object. The system determines the six degrees of freedom pose estimate of the target object based on the image data captured by the camera. The system then determines an estimated point of intersection representing where the line-of-sight intersects with the six degrees of freedom pose estimate of the target object. The system then determines an estimated distance measured between the range-sensing device and the estimated point of intersection. The system calculates an absolute error based on a difference between the actual distance and the estimated distance. In an embodiment, the system also determines a reprojection error introduced by the six degrees of freedom pose estimate of the target object. The system then determines a revised pose estimate of the target object based on the absolute error and, if available, the reprojection error.

The following description is merely exemplary in nature and is not intended to limit the present disclosure, application, or uses.

Referring to FIG. 1, a system **10** for refining a six degrees of freedom pose estimate **8** (seen in FIG. 2) of a target object **12** is illustrated. In the example as shown in FIG. 1, the system **10** is part of an aerial refueling system **14** located at a tail section **16** of a tanker or supply aircraft **18**. The aerial refueling system **14** includes a boom assembly

20 connected to a fuselage **22** of the supply aircraft **18** at an articulating joint **24**. The boom assembly **20** includes a rigid portion **26**, a telescoping extension **28**, and a nozzle **30**. The nozzle **30** of the boom assembly **20** is engaged with a fuel receptacle **32** of a receiver aircraft **34** during a refueling operation. In the example as shown, the receiver aircraft **34**, and in particular the fuel receptacle **32**, represent the target object **12**. Accordingly, the system **10** refines the six degrees of freedom pose estimate **8** (FIG. 2) of the fuel receptacle **32** and the receiver aircraft **34**. The system **10** includes a control module **40** in electronic communication with a camera **42** and a range-sensing device **44**. The camera **42** is positioned in a location to capture image data of the target object **12** (i.e., the fuel receptacle **32** and the receiver aircraft **34**). The control module **40** predicts the six-degree of freedom pose estimate **8** of the target object **12** based on the image data captured by the camera **42**.

Referring to both FIGS. 1 and 2, the range-sensing device **44** is configured to determine an actual distance d between the range-sensing device **44** (shown in FIG. 2) and the target object **12** (i.e., the fuel receptacle **32**). The actual distance d represents a single one-dimensional measurement determined by the range-sensing device **44**. As explained below, the control module **40** of the system **10** determines an absolute error associated with the six degrees of freedom pose estimate **8** of the target object **12** based on the actual distance d . In an embodiment, the control module **40** determines a revised six degrees of freedom pose estimate of the target object **12** based on the absolute error. As explained also below, in another embodiment the control module **40** also determines a reprojection error associated with estimating the six degrees of freedom pose estimate **8**, and then determines the revised six degrees of freedom pose estimate based on both the reprojection error and the absolute error.

In the example as shown in FIG. 1, the control module **40** determines a position and an orientation of the boom assembly **20** based on the revised six degrees of freedom pose estimate. However, it is to be appreciated that FIG. 1 is merely exemplary in nature and the system **10** is not limited to the aerial refueling system **14**. Indeed, the system **10** may be used in a variety of other applications where a six degrees of freedom pose

estimate of a rigid object is estimated. As seen in FIG. 2, the system 10 includes an extendable arm 38. The extendable arm 38 is represented by the boom assembly 20 shown in FIG. 1, however, it is to be appreciated that the extendable arm 38 is not limited to the boom assembly 20. For example, in another embodiment, the extendable arm 38 is a robotic arm that grasps and manipulates objects. In this example, the control module 40 determines a position and an orientation of the extendable arm 38 based on the revised six degrees of freedom pose estimate as the extendable arm 38 grasps and manipulates an object.

The camera 42 sends a video or image feed to the control module 40. In the non-limiting embodiment as shown in FIG. 1, the camera 42 is mounted to an underside 46 of the fuselage 22 of the supply aircraft 18. However, it is to be appreciated that the position of the camera 42 is not limited to any specific location on the receiver aircraft 34. Instead, the camera 42 is positioned in any location where a field-of-view 50 of the camera 42 captures the target object 12. For example, in the embodiment as shown in FIG. 1, the camera 42 may be mounted along any number of locations along the underside 46 of the fuselage 22 of the supply aircraft 18 as long as the field-of-view 50 of the camera 42 captures the fuel receptacle 32 and the receiver aircraft 34.

The range-sensing device 44 is any type of device for determining a distance to a specific target location without the need for physical contact. The range-sensing device 44 includes, but is not limited to, a laser range finder, an ultrasonic sensor, an infrared distance sensor, a light detection and ranging distance (lidar) sensor, or a sonar sensor. In the non-limiting embodiment as shown in FIGS. 1, the range-sensing device 44 is mounted statically to a distal end 48 of the rigid portion 26 of the boom assembly 20. In the example as seen in FIG. 2, the range-sensing device 44 is also mounted to a distal end 52 of the extendable arm 38. As seen in both FIGS. 1 and 2, the line-of-sight L of the range-sensing device 44 is aligned with a longitudinal axis A-A of the extendable arm 38 (or the boom assembly 20). Accordingly, the control module 40 determines the position and the line-of-sight L of the range-sensing device 44 based on the movement of the extendable arm 38. For example, if the extendable arm 38 is a robotic arm, then

the control module **40** determines the position and the line-of-sight L based on the robotic arm's joint angles.

It is to be appreciated that the range-sensing device **44** may be located in a variety of locations other than the rigid portion **26** of the boom assembly **20** as seen in FIG. **1** or
5 on the extendable arm **38** as seen in FIG. **2**. In other words, the line-of-sight L of the range-sensing device **44** may not be aligned with the longitudinal axis A-A of the extendable arm **38**. Instead, the range-sensing device **44** is positioned in any location where the line-of-sight L of the range-sensing device **44** intersects with the target object **12**. For example, in an alternative embodiment, the range-sensing device **44** is
10 mounted directly adjacent to the camera **42** on the underside **46** of the fuselage **22** of the supply aircraft **18**.

Referring to FIGS. **1** and **2**, the position, orientation, and intrinsic parameters of the camera **42** are determined in a preliminary off-line camera calibration procedure or, alternatively, the intrinsic parameters are saved in a memory **1034** (FIG. **5**) of the control
15 module **40**. Some examples of the intrinsic parameters of the camera **42** include, but are not limited to, resolution and aspect ratio. A three-dimensional representation **54** of the target object **12** is shown in phantom line in FIG. **2**. The three-dimensional representation **54** is also saved in the memory **1034** of the control module **40** as well. The control module **40** is configured to predict the six degrees of freedom pose estimate
20 **8** of the target object **12** (i.e., the fuel receptacle **32** and the receiver aircraft **34**) based on the image data captured by the camera **42** using any number of pose estimation approaches. For example, in one non-limiting embodiment, the control module **40** determines the six-degree of freedom pose estimate **8** of the target object **12** based on a perspective-n-point algorithm.

25 Referring to both FIGS. **1** and **3**, the perspective-n-point algorithm estimates the six degrees of freedom pose estimate **8** (FIG. **2**) of the target object **12** based on a plurality of two-dimensional keypoints **60** and a plurality of three-dimensional keypoints **62** (the two-dimensional keypoints **60** are shown as circles and the three-dimensional keypoints **62** are shown as crosses). Specifically, the perspective-n-point algorithm requires three

or more three-dimensional keypoints **62** disposed on the target object **12**. The three-dimensional keypoints **62** are detected by the control module **40** based on the image data captured by the camera **42**. The control module **40** detects the three or more three-dimensional keypoints **62** on the target object **12** (i.e., the fuel receptacle **32**) in each
5 image frame of the image feed received from the camera **42**. The control module **40** then predicts a corresponding two-dimensional keypoint **60** for each of the plurality of three-dimensional keypoints **62** using a deep neural network. The control module **40** then aligns the plurality of three-dimensional keypoints **62** with the corresponding two-dimensional keypoints **60**, and then predicts the six degrees of freedom pose estimate
10 based on the three-dimensional keypoints **62**.

It is to be appreciated that while a perspective-n-point algorithm is described, other pose estimation processes may also be used to determine the six degrees of freedom pose estimate. For example, in an alternative approach, the six degrees of freedom pose estimate is determined based on two or more point-tangent correspondences between
15 the three-dimensional keypoints **62** and the two-dimensional keypoints **60**. In another embodiment, the six degrees of freedom pose estimate is determined by deep neural network that determines the six degrees of freedom pose estimate directly based on the image data captured by the camera **42**.

Referring back to FIGS. **1** and **2**, once the control module **40** determines the six degrees
20 of freedom pose estimate **8**, the control module **40** then aligns the longitudinal axis A-A of the extendable arm **38** in a direction towards the target object **12** (i.e., the receiver aircraft **34**). It is to be appreciated that the initial six degrees of freedom pose estimate **8** as described above may be a locally coarse estimate, and the longitudinal axis A-A of the extendable arm **38** (and therefore the line-of sight L of the range-sensing device **44**)
25 only needs to generally intersect with the target object **12** (i.e., the receiver aircraft **34**). In the example as shown in FIGS. **1** and **2**, since the nozzle **30** of the boom assembly **20** engages with the fuel receptacle **32** of the receiver aircraft **34** during a refueling operation, the range-sensing device **44** projects the line-of-sight L towards the fuel receptacle **32**.

The range-sensing device **44** is configured to determine the actual distance d . Referring specifically to FIG. **2**, the actual distance d is measured between the range-sensing device **44** and an actual point of intersection W' . The line-of-sight L projected by the range-sensing device **44** intersects with the target object **12** (i.e., the fuel receptacle **32**) at the actual point of intersection W' . Thus, the actual distance d represents a one-dimensional depth measurement between the range-sensing device **44** and the target object **12**. It is to be appreciated that prior to the pose refinement process using the range-sensing device **44**, depth estimates, such as estimates of the distance d , are associated with the greatest amount of error when compared to length and height measurements. This is because the initial six degrees of freedom pose estimate is based on a perspective of the camera **42**, which lacks depth cues. Furthermore, it is also to be appreciated that the position of the actual point of intersection W' upon a surface **70** of the receiver aircraft **34** need not be known. Finally, it is also to be appreciated that the actual point of intersection W' may lie anywhere upon the surface **70** of the receiver aircraft **34**.

Referring specifically to FIG. **2**, the control module **40** then determines an estimated point of intersection W . The estimated point of intersection W represents where the line-of-sight L intersects with the six degrees of freedom pose estimate **8** of the target object **12**. As seen in FIG. **2**, the estimated point of intersection W is offset from the actual point of intersection W' because of the coarseness of the initial six degrees of freedom pose estimate **8**. The control module **40** then determines an estimated distance D measured between the range-sensing device **44** and the estimated point of intersection W . The control module **40** then calculates the absolute error associated with the six degrees of freedom pose estimate **8** of the target object **12** based on a difference between the actual distance d and the estimated distance D . Specifically, the absolute error is expressed in Equation **1** as:

$$\|W - (O + dL)\|^2 \quad \text{Equation 1}$$

where O represents a base of the extendable arm **38**, which is shown in FIG. **2**, and $W'=(O + dL)$. In other words, Equation **1** may be expressed as $\|W - W'\|^2$.

In addition to the absolute error, in one embodiment the control module **40** also determines the reprojection error introduced by the six degrees of freedom pose estimate **8**. Specifically, the reprojection error represents a difference between a plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints **60** shown in FIG. **3**. The plurality of two-dimensional pixel positions are determined by projecting the three-dimensional keypoints **62** (FIG. **2**) into two-dimensional space. It is to be appreciated that the three-dimensional keypoints **62** shown in FIG. **3** are represented in camera space. The camera space refers to a three-dimensional coordinate system having an origin represented by a center C of the camera **42** (FIG. **1**), where a user defines the three axes (i.e., x, y, and z). Thus, the three-dimensional keypoints **62** indicate how the target object **12** appears with respect to the perspective view of the camera **42**. For example, if the target object **12** is located **20** meters straight in front of the camera **42**, then a z-coordinate (which is assumed to be aligned with a line-of-sight of the camera **42**) of the resulting three-dimensional keypoint **62** would be **20** meters. It is also to be appreciated that when the three-dimensional keypoints **62** are projected into the two-dimensional space to represent the two-dimensional pixel locations, the three-dimensional keypoints **62** are flattened along a depth dimension. However, the range-sensing device **44** is aligned with the depth dimension, and therefore adds information that is otherwise missing from the two-dimensional pixel locations.

The reprojection error of the perspective-n-point algorithm is expressed in Equation **2** as:

$$\|P(V[RX + t]) - y'\|^2 \quad \text{Equation 2}$$

where P represents a camera projection function of the camera **42**, V represents a coordinate transform matrix, R represents a rotation matrix representing the three orientation components (pitch, roll, and yaw) of the six degrees of freedom parameters, X represents a matrix containing the plurality of three-dimensional keypoints **62**, t represents a vector representing the positional components (x, y, and z), of the six degrees of freedom parameters, and y' represents the two-dimensional keypoints **60** (shown in FIG. **3**). The camera projection function of the camera **42** converts the three-

dimensional keypoints **62**, which are represented by the camera space, into the two-dimensional dimensional space. The coordinate transform matrix V converts the three-dimensional keypoints **62** represented in model space into the camera space. The model space represents a three-dimensional coordinate system having an origin **74** (seen in FIG. **2**) that is located at a center of the three-dimensional representation **54**. The vector t contains the positional components of the six degrees of freedom parameters and defines the translation between origin **74** of the model space and the center C of the camera space. Similarly, the rotation matrix R contains the orientation components of the six degrees of freedom parameters and defines the rotation between the axes defined in model space and the axes defined in camera space.

In one embodiment, the control module **40** determines the revised six degrees of freedom pose estimate based on just the absolute error. In this embodiment, the control module **40** determines a minimum value of the absolute error, and then calculates the revised six degrees of freedom pose estimate produces or results in the minimum value of the absolute error. In other words, control module **40** determines a value for the refined six degrees of freedom pose estimate associated with the least amount of absolute error. The minimum value of the absolute error is expressed in Equation **3** as:

$$\min_{\theta} \|W - (O + dL)\|^2 \quad \text{Equation 3}$$

where θ represents the six degrees of freedom pose estimate of the target object **12**, i.e., $\theta = [x, y, z, \text{pitch}, \text{roll}, \text{yaw}]$.

In another embodiment, the control module **40** determines the revised six degrees of freedom pose estimate **8** based on both the absolute error and the reprojection error. In an embodiment, the control module **40** determines the revised six degrees of freedom pose estimate by first determining a minimum value of a weighted sum, where the weighted sum combines the absolute error and the reprojection error together. The weighted sum is expressed in Equation **4** as:

$$\min_{\theta} \|P(V[RX + t]) - y'\|^2 + \lambda^2 \|W - (O + dL)\|^2 \quad \text{Equation 4}$$

where λ represents a use-defined scale factor. Changing a value of the scale factor λ results in a specific implementation to account for the relative accuracies of the range-

sensing device **44** and the six degree of freedom pose estimate **8**. The minimum value of the weighted sum is determined based on a non-linear least square algorithm. There are several types of non-linear least square algorithms available that may be used to determine the minimum value of the weighted sum. Some examples of non-linear least square algorithms include, but are not limited to, Gauss-Newton methods, a Levenberg–Marquardt algorithm, a gradient method such as a conjugate-gradient method, and direct search methods such as a Nelder-Mead simplex search.

FIGS. **4A-4B** is an exemplary process flow diagram illustrating a method **200** for refining the six degrees of freedom pose estimate **8** (FIG. **2**) of the target object **12**. Referring generally to FIGS. **1-4A**, the method **200** begins at block **202**. In block **202**, the camera **42** captures the image data of the target object **12**. The method **200** may then proceed to block **204**.

In block **204**, the range-sensing device **44** determines the actual distance d . As mentioned above, the actual distance d is measured between the range-sensing device **44** and the actual point of intersection W' (seen in FIG. **2**), where the range-sensing device **44** projects the line-of-sight L that intersects with the target object **12** at the actual point of intersection W' . The method **200** may then proceed to block **206**.

In block **206**, the control module **40** predicts, based on the image data of the target object **12**, the six degrees of freedom pose estimate **8** of the target object **12**. As explained above, the six degrees of freedom pose estimate **8** may be determined using any number of pose estimation approaches such as, for example, the perspective- n -point algorithm. The method **200** may then proceed to block **208**.

In block **208**, the control module **40** determines the estimated point of intersection W (FIG. **2**) representing where the line-of-sight L intersects with the six degrees of freedom pose estimate **8** of the target object **12**. The method **200** may then proceed to block **210**.

In block **210**, the control module **40** determines the estimated distance D measured between the range-sensing device **44** and the estimated point of intersection W . The method **200** may then proceed to block **212**.

5 In block **212**, the control module **40** calculates the absolute error associated with the six degrees of freedom pose estimate **8** of the target object **12** based on a difference between the actual distance and the estimated distance. The method **200** may then proceed to decision block **214**.

10 In decision block **214**, the revised six degree of freedom estimate is determined based on either the absolute error alone or, in the alternative, based on the absolute error and the reprojection error. If the control module **40** determines the revised six degree of freedom pose estimate is determined based on the absolute error alone, then the method proceeds to block **216**.

15 In block **216**, the control module **40** calculates the minimum value of the absolute error. As explained above, the control module **40** calculates the absolute error associated with the six degrees of freedom pose estimate **8** of the target object **12** based on a difference between the actual distance d and the estimated distance D and is expressed in Equation 1. The method **200** may then proceed to block **218**.

20 In block **218**, the control module **40** calculates the revised six degrees of freedom pose estimate, where the revised six degree of freedom pose estimate produces the minimum value of the absolute error. The method **200** may then terminate.

25 Referring back to decision block **214**, if the revised six degrees of freedom pose estimate is not determined based on the absolute error alone, then the method **200** proceeds to block **220**, which is shown in FIG. 4B. Specifically, if the control module **40** determines the revised six degree of freedom pose estimate based on both the absolute error and the reprojection error then the method **200** proceeds to block **220**.

In block **220**, the control module **40** determines the reprojection error introduced by the six degrees of freedom pose estimate **8** of the target object **12**. As explained above,

the reprojection error represents the difference between the plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints **60** shown in FIG. **3**. It is to be appreciated that a process flow diagram for determining the reprojection error is shown in FIG. **4C**. The method **200** may then proceed to block **222**.

- 5 In block **222**, the control module **40** determines the minimum value of the weighted sum, where the weighted sum combines the absolute error and the reprojection error together. The minimum value of the weighted sum may be determined using a variety of different approaches such as, for example, the Levenberg–Marquardt algorithm. The method **200** may then proceed to block **224**.
- 10 In block **224**, the control module **40** calculates the revised six degrees of freedom pose estimate, where the revised six degrees of freedom pose estimate produces the minimum value of the weighted sum. In an embodiment, the method **200** may then proceed to block **226**.

In block **226**, in one embodiment, the disclosed system **10** includes the extendable arm **38** (seen in FIG. **1** as the boom assembly **20** and in FIG. **2**). Accordingly, in block **226**, in response to determining the revised six degrees of freedom pose estimate, the control module **40** determines a position and an orientation of the extendable arm **38** based on the revised six degrees of freedom pose estimate. The method **200** may then terminate.

Referring now to FIG. **4C**, a process flow diagram illustrating a method **250** for determining the reprojection error is now described. Referring to FIGS. **1**, **3**, and **4C**, the method **250** begins at block **252**. In block **252**, the control module **40** detects the plurality of three-dimensional keypoints **62** that correspond to the target object **12** based on the image data captured by the camera **42**. The method **250** may then proceed to block **254**.

- 25 The block **254**, a deep neural network predicts the corresponding two-dimensional keypoint **60** for each of the plurality of three-dimensional keypoints **62**. The method **250** may then proceed to block **256**.

In block **256**, the control module **40** aligns the plurality of three-dimensional keypoints **62** with the plurality of two-dimensional keypoints **60**. The method **250** may then proceed to block **258**.

5 In block **258**, the control module **40** predicts the six degrees of freedom pose estimate **8** based on the three-dimensional keypoints **62**. The method **250** may then proceed to block **260**.

In block **260**, the control module **40** determines the plurality of two-dimensional pixel positions by projecting the plurality of three-dimensional keypoints **62** into two-dimensional space. The method **250** may then proceed to block **262**.

10 In block **262**, the control module **40** determines the difference between a plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints **60**, where the difference between the plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints **60** represent the reprojection error. The method **250** may then terminate.

15 Referring generally to the figures, the disclosed system provides various technical effects and benefits. Specifically, the disclosed system utilizes a single one-dimensional measurement from the range-sensing device for refining the six degrees of freedom pose estimate as opposed to a two-dimensional scan or, alternatively, a three-dimensional depth map. Accordingly, the disclosed system does not require significant
20 processing and memory allocation requirements or a laser range finder having precisely manufactured moving parts like some conventional systems currently available. Additionally, the disclosed system does not require specialized calibration patterns or correspondence markers during the refinement process, unlike some conventional systems currently available as well.

25 Referring to FIG. **5**, the control module **40** of FIG. **1** may be implemented on one or more computer devices or systems, such as exemplary computer system **1030**. The computer system **1030** includes a processor **1032**, a memory **1034**, a mass storage memory device **1036**, an input/output (I/O) interface **1038**, and a Human Machine

Interface (HMI) **1040**. The computer system **1030** is operatively coupled to one or more external resources **1042** via the network **1026** or I/O interface **1038**. External resources may include, but are not limited to, servers, databases, mass storage devices, peripheral devices, cloud-based network services, or any other suitable computer resource that may be used by the computer system **1030**.

The processor **1032** includes one or more devices selected from microprocessors, micro-controllers, digital signal processors, microcomputers, central processing units, field programmable gate arrays, programmable logic devices, state machines, logic circuits, analog circuits, digital circuits, or any other devices that manipulate signals (analog or digital) based on operational instructions that are stored in the memory **1034**. Memory **1034** includes a single memory device or a plurality of memory devices including, but not limited to, read-only memory (ROM), random access memory (RAM), volatile memory, non-volatile memory, static random-access memory (SRAM), dynamic random-access memory (DRAM), flash memory, cache memory, or any other device capable of storing information. The mass storage memory device **1036** includes data storage devices such as a hard drive, optical drive, tape drive, volatile or non-volatile solid-state device, or any other device capable of storing information.

The processor **1032** operates under the control of an operating system **1046** that resides in memory **1034**. The operating system **1046** manages computer resources so that computer program code embodied as one or more computer software applications, such as an application **1048** residing in memory **1034**, may have instructions executed by the processor **1032**. In an alternative example, the processor **1032** may execute the application **1048** directly, in which case the operating system **1046** may be omitted. One or more data structures **1049** also reside in memory **1034**, and may be used by the processor **1032**, operating system **1046**, or application **1048** to store or manipulate data.

The I/O interface **1038** provides a machine interface that operatively couples the processor **1032** to other devices and systems, such as the network **1026** or external resource **1042**. The application **1048** thereby works cooperatively with the network **1026** or external resource **1042** by communicating via the I/O interface **1038** to provide

the various features, functions, applications, processes, or modules comprising examples of the disclosure. The application **1048** also includes program code that is executed by one or more external resources **1042**, or otherwise rely on functions or signals provided by other system or network components external to the computer system **1030**. Indeed, given the nearly endless hardware and software configurations possible, persons having ordinary skill in the art will understand that examples of the disclosure may include applications that are located externally to the computer system **1030**, distributed among multiple computers or other external resources **1042**, or provided by computing resources (hardware and software) that are provided as a service over the network **1026**, such as a cloud computing service.

The HMI **1040** is operatively coupled to the processor **1032** of computer system **1030** in a known manner to allow a user to interact directly with the computer system **1030**. The HMI **1040** may include video or alphanumeric displays, a touch screen, a speaker, and any other suitable audio and visual indicators capable of providing data to the user. The HMI **1040** also includes input devices and controls such as an alphanumeric keyboard, a pointing device, keypads, pushbuttons, control knobs, microphones, etc., capable of accepting commands or input from the user and transmitting the entered input to the processor **1032**.

A database **1044** may reside on the mass storage memory device **1036** and may be used to collect and organize data used by the various systems and modules described herein. The database **1044** may include data and supporting data structures that store and organize the data. In particular, the database **1044** may be arranged with any database organization or structure including, but not limited to, a relational database, a hierarchical database, a network database, or combinations thereof. A database management system in the form of a computer software application executing as instructions on the processor **1032** may be used to access the information or data stored in records of the database **1044** in response to a query, where a query may be dynamically determined and executed by the operating system **1046**, other applications **1048**, or one or more modules.

Further illustrative and non-exclusive examples according to, the disclosure are described in the following paragraphs:

In one embodiment, there is provided a system for refining a six degrees of freedom pose estimate of a target object based on a one-dimensional measurement. The system
5 includes a camera configured to capture image data of the target object, and a range-sensing device configured to determine an actual distance (d) measured between the range-sensing device and an actual point of intersection (W'). The range-sensing device projects a line-of-sight (L) that intersects with the target object at the actual point of intersection (W'). The system further includes one or more processors in electronic
10 communication with the camera and the range-sensing device. The system further includes memory coupled to the one or more processors, the memory storing data into one or more databases and program code that, when executed by the one or more processors. The system is caused to predict, based on the image data of the target object, the six degrees of freedom pose estimate of the target object, determine an
15 estimated point of intersection (W) representing where the line-of-sight (L) intersects with the six degrees of freedom pose estimate of the target object; determine an estimated distance (D) measured between the range-sensing device and the estimated point of intersection (W); calculate an absolute error associated with the six degrees of freedom pose estimate of the target object based on a difference between the actual
20 distance and the estimated distance (D). The system is further caused to calculate a revised six degrees of freedom pose estimate of the target object based on at least the absolute error.

The one or more processors may execute instructions to: calculate a minimum value of the absolute error; and calculate the revised six degrees of freedom pose estimate. The
25 revised six degree of freedom pose may estimate produces the minimum value of the absolute error.

The one or more processors may further execute instructions to: determine a reprojection error introduced by the six degrees of freedom pose estimate of the target object; determine a minimum value of a weighted sum. The weighted sum may combine

the absolute error and the reprojection error together; and calculate the revised six degrees of freedom pose estimate. The revised six degree of freedom pose may estimate produces the minimum value of the weighted sum.

5 The one or more processors may further determine the minimum value of the weighted sum based on a non-linear least square algorithm.

The one or more processors may further execute instructions to: determine the six degrees of freedom pose estimate of the target object based on a perspective-n-point algorithm.

10 The one or more processors may further execute instructions to: detect a plurality of three-dimensional keypoints that correspond to the target object based on the image data captured by the camera; predict, by a deep neural network, a corresponding two-dimensional keypoint for each of the plurality of three-dimensional keypoints; align the plurality of three-dimensional keypoints with a plurality of two-dimensional keypoints; and predict the six degrees of freedom pose estimate based on the three-dimensional
15 keypoints.

The one or more processors may further execute instructions to: determine a plurality of two-dimensional pixel positions by projecting the plurality of three-dimensional keypoints into two-dimensional space; and determine a difference between a plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints. The
20 difference between the plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints represent a reprojection error.

The system may further include an extendable arm defining a longitudinal axis. The longitudinal axis of the extendable arm may be aligned with the line-of-sight (L) of the range-sensing device.

25 The extendable arm may be a boom assembly of an aerial refueling system or a robotic arm.

The range-sensing device may be mounted statically to the extendable arm.

The one or more processors may execute instructions to: in response to determining the revised six degrees of freedom pose estimate, determine a position and an orientation of the extendable arm based on the revised six degrees of freedom pose estimate.

- 5 The range-sensing device may be a laser range finder, an ultrasonic sensor, an infrared distance sensor, a light detection and ranging distance (lidar) sensor, or a sonar sensor.

The actual distance (d) may represent a one-dimensional depth measurement between the range-sensing device and the target object.

In another embodiment, there is provided an aerial refueling system for a supply aircraft
10 the aerial refueling system. The system includes a boom assembly including a nozzle;
and a system for determining a revised six degrees of freedom pose estimate of a fuel
receptacle located on a receiver aircraft. The nozzle of the boom assembly configured
to engage with a fuel receptacle of the receiver aircraft during a refueling operation. The
system includes: a camera configured to capture image data of the receiver aircraft and
15 the fuel receptacle. The system further includes a range-sensing device configured to
determine an actual distance (d) measured between the range-sensing device and an
actual point of intersection (W'). The range-sensing device projects a line-of-sight (L)
that intersects with the receiver aircraft at the actual point of intersection (W'); The
system further includes one or more processors in electronic communication with the
20 camera and the range-sensing device; and a memory coupled to the one or more
processors, the memory storing data into one or more databases and program code
that, when executed by the one or more processors. The system is caused to predict,
based on the image data of the fuel receptacle located on a receiver aircraft, the six
degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft;
25 determine an estimated point of intersection (W) representing where the line-of-sight (L)
intersects with the six degrees of freedom pose estimate of the receiver aircraft;
determine an estimated distance (D) measured between the range-sensing device and
the estimated point of intersection (W); calculate an absolute error associated with the
six degrees of freedom pose estimate of the fuel receptacle located on the receiver

aircraft based on a difference between the actual distance (d) and the estimated distance (D). The system is further caused to calculate a revised six degrees of freedom pose estimate based on at least the absolute error.

5 The one or more processors may further execute instructions to: calculate a minimum value of the absolute error; and calculate the revised six degrees of freedom pose estimate. The revised six degree of freedom pose may estimate produces the minimum value of the absolute error.

10 The one or more processors may further execute instructions to: determine a reprojection error introduced by the six degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft; determine a minimum value of a weighted sum. The weighted sum may combine the absolute error and the reprojection error together; and may calculate the revised six degrees of freedom pose estimate. The revised six degree of freedom pose may estimate produces the minimum value of the weighted sum.

15 In another embodiment, there is provided the method for refining a six degrees of freedom pose estimate of a target object. The method involves: capturing, by a camera, image data of the target object; determining, by a range-sensing device, an actual distance (d) measured between the range-sensing device and an actual point of intersection (W'). The range-sensing device projects a line-of-sight (L) that intersects
20 with the target object at the actual point of intersection (W'); predicting, based on the image data of the target object, the six degrees of freedom pose estimate of the target object; determining an estimated point of intersection (W) representing where the line-of-sight (L) intersects with the six degrees of freedom pose estimate of the target object; determining an estimated distance (D) measured between the range-sensing device
25 and the estimated point of intersection (W); calculating an absolute error associated with the six degrees of freedom pose estimate of the target object based on a difference between the actual distance (d) and the estimated distance (D); and calculate a revised six degree of freedom pose estimate based on at least the absolute error.

The method may further involve: calculating a minimum value of the absolute error; and calculating the revised six degrees of freedom pose estimate. The revised six degree of freedom pose may estimate produces the minimum value of the absolute error.

5 The method may further involve: determining a reprojection error introduced by the six degrees of freedom pose estimate of the target object; determining a minimum value of a weighted sum. The weighted sum may combine the absolute error and the reprojection error together; and calculating the revised six degrees of freedom pose estimate. The revised six degree of freedom pose may estimate produces the minimum value of the weighted sum.

10 The six degrees of freedom pose may estimate of the target object is determined based on a perspective-n-point algorithm.

The description herein is merely exemplary in nature and variations that do not depart from the gist of the teachings herein are intended to be within the scope of the present disclosure. Such variations are not to be regarded as a departure from the spirit and
15 scope of the present teachings.

EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A system for refining a six degrees of freedom pose estimate of a target object based on a one-dimensional measurement, the system comprising:

5 a camera configured to capture image data of the target object;

a range-sensing device configured to determine an actual distance (d) measured between the range-sensing device and an actual point of intersection (W'), wherein the range-sensing device projects a line-of-sight (L) that intersects with the target object at the actual point of intersection (W');

10 one or more processors in electronic communication with the camera and the range-sensing device; and

a memory coupled to the one or more processors, the memory storing data into one or more databases and program code that, when executed by the one or more processors, causes the system to:

15 predict, based on the image data of the target object, the six degrees of freedom pose estimate of the target object;

determine an estimated point of intersection (W) representing where the line-of-sight (L) intersects with the six degrees of freedom pose estimate of the target object;

20 determine an estimated distance (D) measured between the range-sensing device and the estimated point of intersection (W);

calculate an absolute error associated with the six degrees of freedom pose estimate of the target object based on a difference between the actual distance (d) and the estimated distance (D); and

calculate a revised six degrees of freedom pose estimate of the target object based on at least the absolute error.

2. The system of claim 1, wherein the one or more processors execute instructions to:

5 calculate a minimum value of the absolute error; and

calculate the revised six degrees of freedom pose estimate, wherein the revised six degree of freedom pose estimate produces the minimum value of the absolute error.

- 10 3. The system of claim 1 or 2, wherein the one or more processors execute instructions to:

determine a reprojection error introduced by the six degrees of freedom pose estimate of the target object;

determine a minimum value of a weighted sum, wherein the weighted sum combines the absolute error and the reprojection error together; and

15 calculate the revised six degrees of freedom pose estimate, wherein the revised six degree of freedom pose estimate produces the minimum value of the weighted sum.

4. The system of claim 3, wherein the one or more processors determine the minimum value of the weighted sum based on a non-linear least square algorithm.

- 20 5. The system of any one of claims 1-4, wherein the one or more processors execute instructions to:

determine the six degrees of freedom pose estimate of the target object based on a perspective-n-point algorithm.

6. The system of claim 5, wherein the one or more processors execute instructions to:

detect a plurality of three-dimensional keypoints that correspond to the target object based on the image data captured by the camera;

5 predict, by a deep neural network, a corresponding two-dimensional keypoint for each of the plurality of three-dimensional keypoints;

align the plurality of three-dimensional keypoints with a plurality of two-dimensional keypoints; and

10 predict the six degrees of freedom pose estimate based on the three-dimensional keypoints.

7. The system of claim 6, wherein the one or more processors execute instructions to:

determine a plurality of two-dimensional pixel positions by projecting the plurality of three-dimensional keypoints into two-dimensional space; and

15 determine a difference between a plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints, wherein the difference between the plurality of two-dimensional pixel positions and the plurality of two-dimensional keypoints represent a reprojection error.

20 8. The system of any one of claims 1-7, further comprising an extendable arm defining a longitudinal axis, wherein the longitudinal axis of the extendable arm is aligned with the line-of-sight (L) of the range-sensing device.

9. The system of claim 8, wherein the extendable arm is a boom assembly of an aerial refueling system or a robotic arm.

25 10. The system of claim 8 or 9, wherein the range-sensing device is mounted statically to the extendable arm.

11. The system of any one of claims 8-10, wherein the one or more processors execute instructions to:

in response to determining the revised six degrees of freedom pose estimate, determine a position and an orientation of the extendable arm based on the revised six degrees of freedom pose estimate.

12. The system of any one of claims 1-11, wherein the range-sensing device is a laser range finder, an ultrasonic sensor, an infrared distance sensor, a light detection and ranging distance (lidar) sensor, or a sonar sensor.

13. The system of any one of claims 1-12, wherein the actual distance (d) represents a one-dimensional depth measurement between the range-sensing device and the target object.

14. An aerial refueling system for a supply aircraft, the aerial refueling system comprising:

a boom assembly including a nozzle; and

a system for determining a revised six degrees of freedom pose estimate of a fuel receptacle located on a receiver aircraft, wherein the nozzle of the boom assembly is configured to engage with a fuel receptacle of the receiver aircraft during a refueling operation, the system comprising:

a camera configured to capture image data of the receiver aircraft and the fuel receptacle;

a range-sensing device configured to determine an actual distance (d) measured between the range-sensing device and an actual point of intersection (W'), wherein the range-sensing device projects a line-of-sight (L) that intersects with the receiver aircraft at the actual point of intersection (W');

one or more processors in electronic communication with the camera and the range-sensing device; and

a memory coupled to the one or more processors, the memory storing data into one or more databases and program code that, when executed by the one or more processors, causes the system to:

5

predict, based on the image data of the fuel receptacle located on a receiver aircraft, the six degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft ;

10

determine an estimated point of intersection (W) representing where the line-of-sight (L) intersects with the six degrees of freedom pose estimate of the receiver aircraft ;

determine an estimated distance (D) measured between the range-sensing device and the estimated point of intersection (W);

15

calculate an absolute error associated with the six degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft based on a difference between the actual distance (d) and the estimated distance (D); and

calculate a revised six degrees of freedom pose estimate based on at least the absolute error.

20 **15.** The aerial refueling system of claim **14**, wherein the one or more processors execute instructions to:

calculate a minimum value of the absolute error; and

calculate the revised six degrees of freedom pose estimate, wherein the revised six degree of freedom pose estimate produces the minimum value of the absolute error.

25

16. The aerial refueling system of claim 14 or 15, wherein the one or more processors execute instructions to:

determine a reprojection error introduced by the six degrees of freedom pose estimate of the fuel receptacle located on the receiver aircraft;

5 determine a minimum value of a weighted sum, wherein the weighted sum combines the absolute error and the reprojection error together; and

10 calculate the revised six degrees of freedom pose estimate, wherein the revised six degree of freedom pose estimate produces the minimum value of the weighted sum.

17. A method for refining a six degrees of freedom pose estimate of a target object, the method comprising:

capturing, by a camera, image data of the target object;

15 determining, by a range-sensing device, an actual distance (d) measured between the range-sensing device and an actual point of intersection (W'), wherein the range-sensing device projects a line-of-sight (L) that intersects with the target object at the actual point of intersection (W');

predicting , based on the image data of the target object, the six degrees of freedom pose estimate of the target object;

20 determining an estimated point of intersection (W) representing where the line-of-sight (L) intersects with the six degrees of freedom pose estimate of the target object ;

determining an estimated distance (D) measured between the range-sensing device and the estimated point of intersection (W);

calculating an absolute error associated with the six degrees of freedom pose estimate of the target object based on a difference between the actual distance (d) and the estimated distance (D); and

5 calculate a revised six degree of freedom pose estimate based on at least the absolute error.

18. The method of claim **17**, further comprising:

calculating a minimum value of the absolute error; and

10 calculating the revised six degrees of freedom pose estimate, wherein the revised six degree of freedom pose estimate produces the minimum value of the absolute error.

19. The method of claim **17** or **18**, further comprising:

determining a reprojection error introduced by the six degrees of freedom pose estimate of the target object;

15 determining a minimum value of a weighted sum, wherein the weighted sum combines the absolute error and the reprojection error together; and

calculating the revised six degrees of freedom pose estimate, wherein the revised six degree of freedom pose estimate produces the minimum value of the weighted sum.

20 **20.** The method of any one of claims **17-19**, wherein the six degrees of freedom pose estimate of the target object is determined based on a perspective-n-point algorithm.

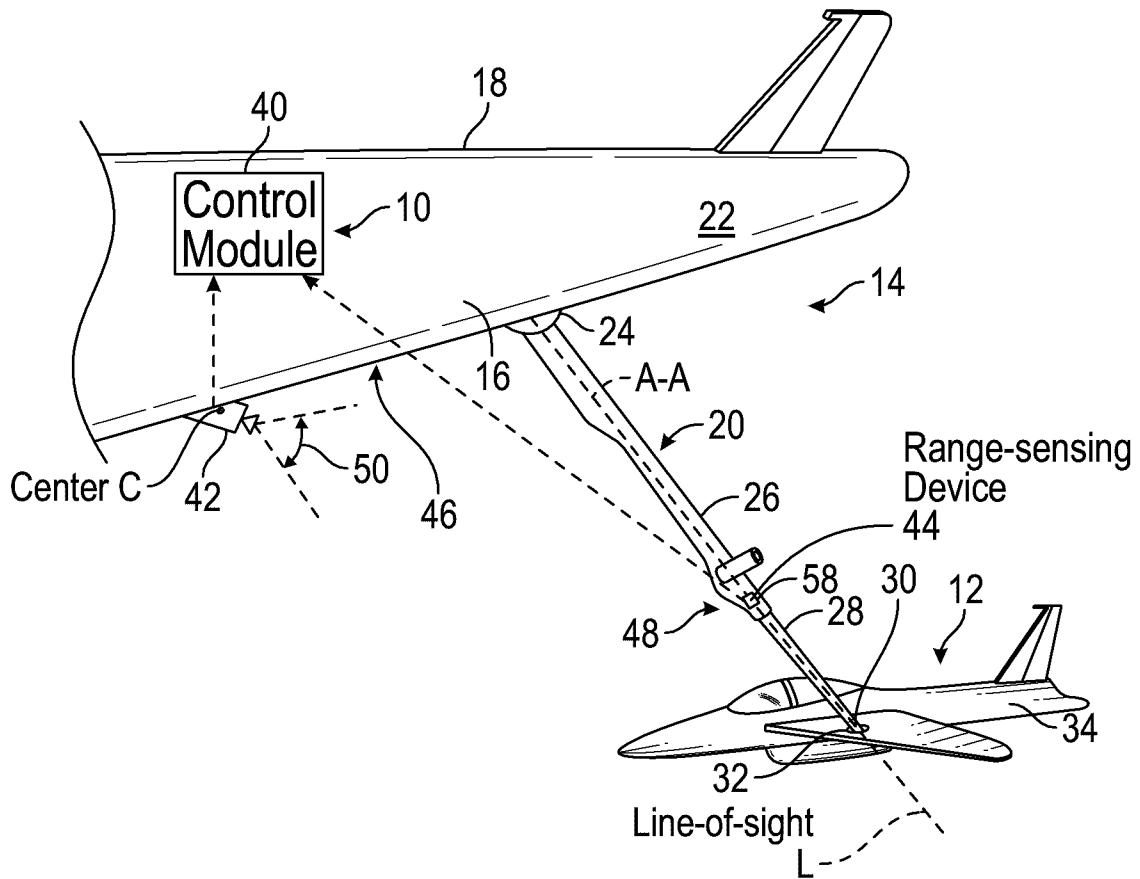


FIG. 1

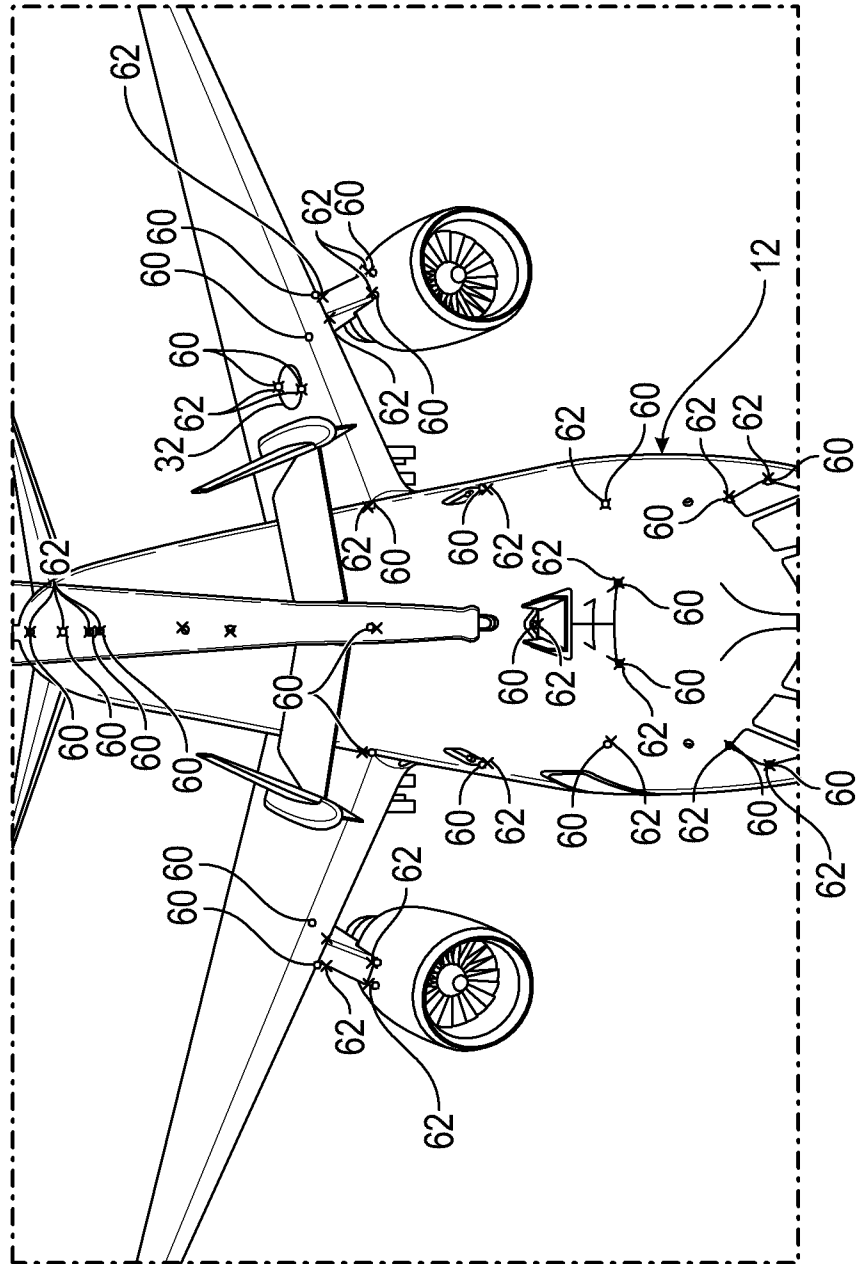


FIG. 3

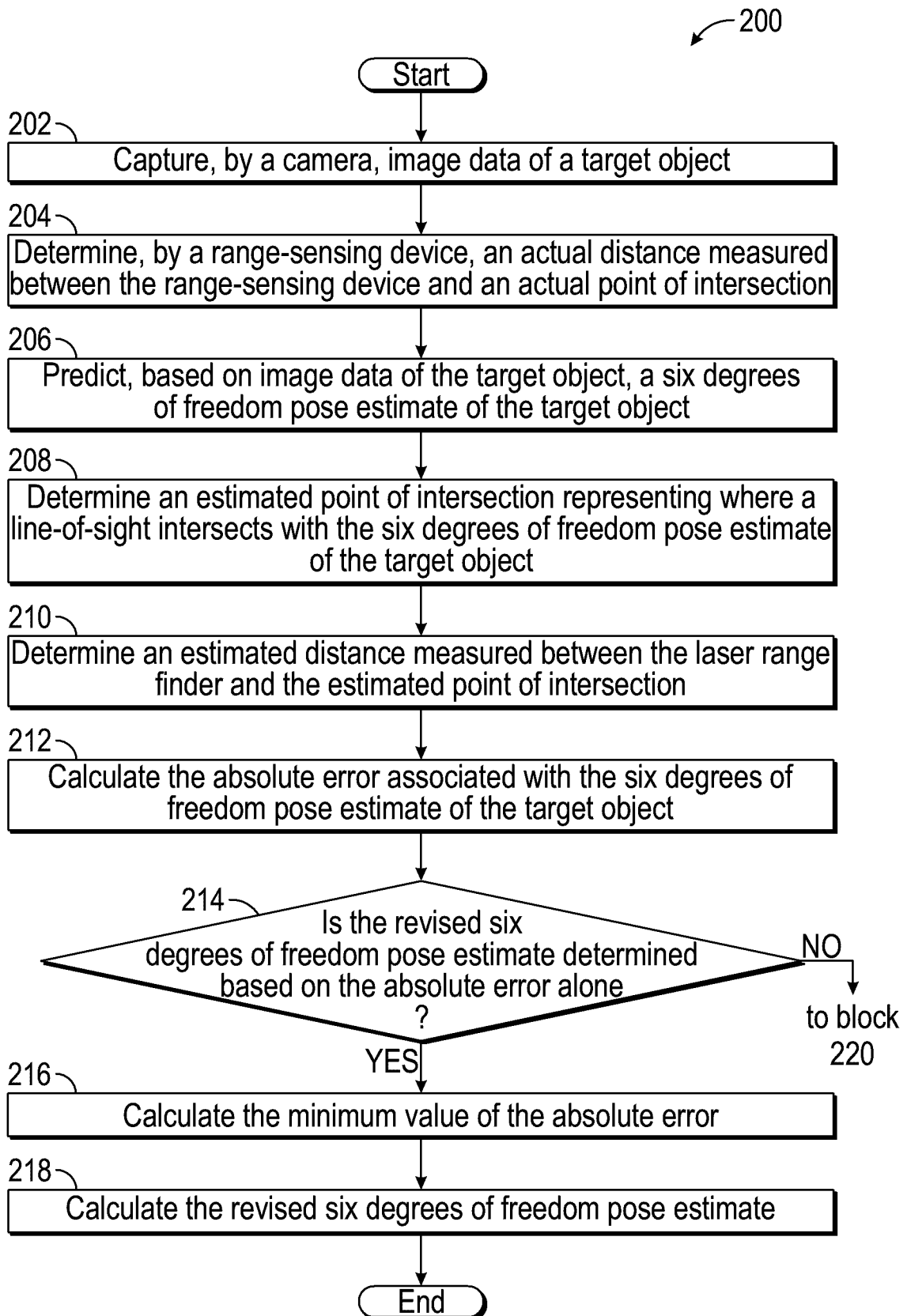


FIG. 4A

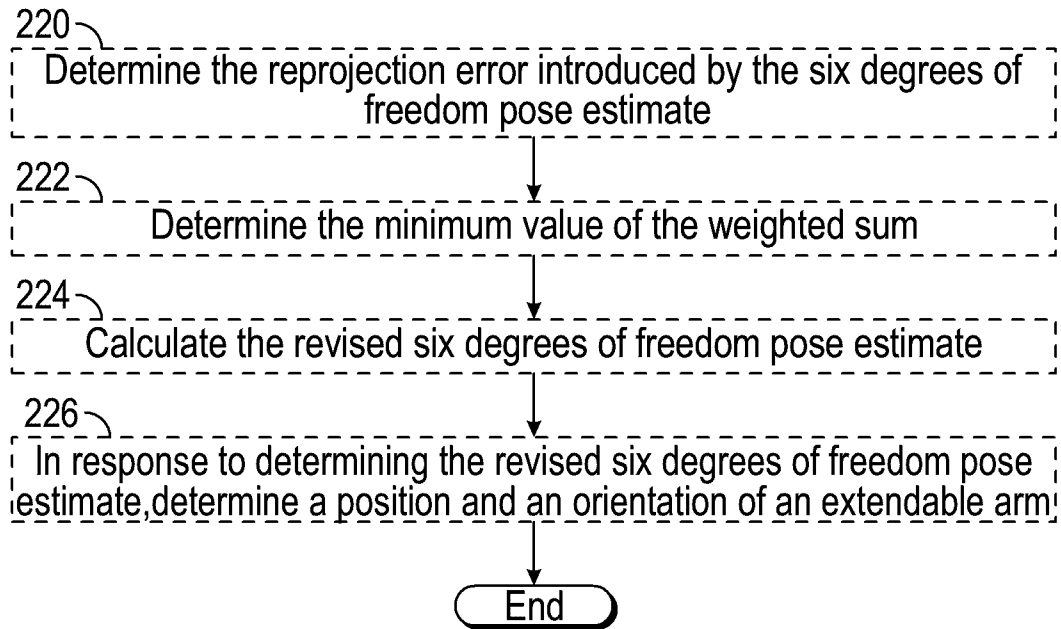


FIG. 4B

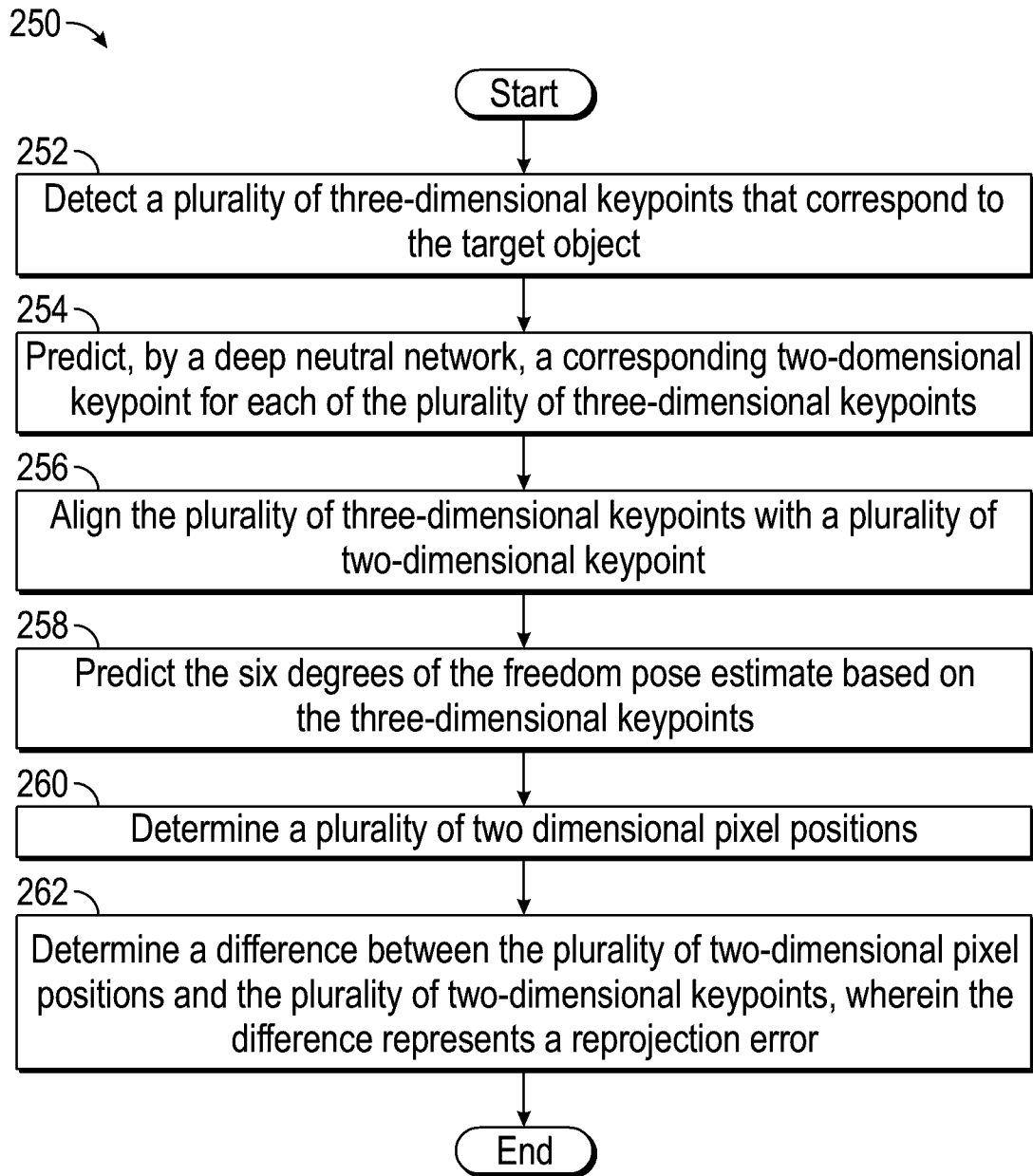


FIG. 4C

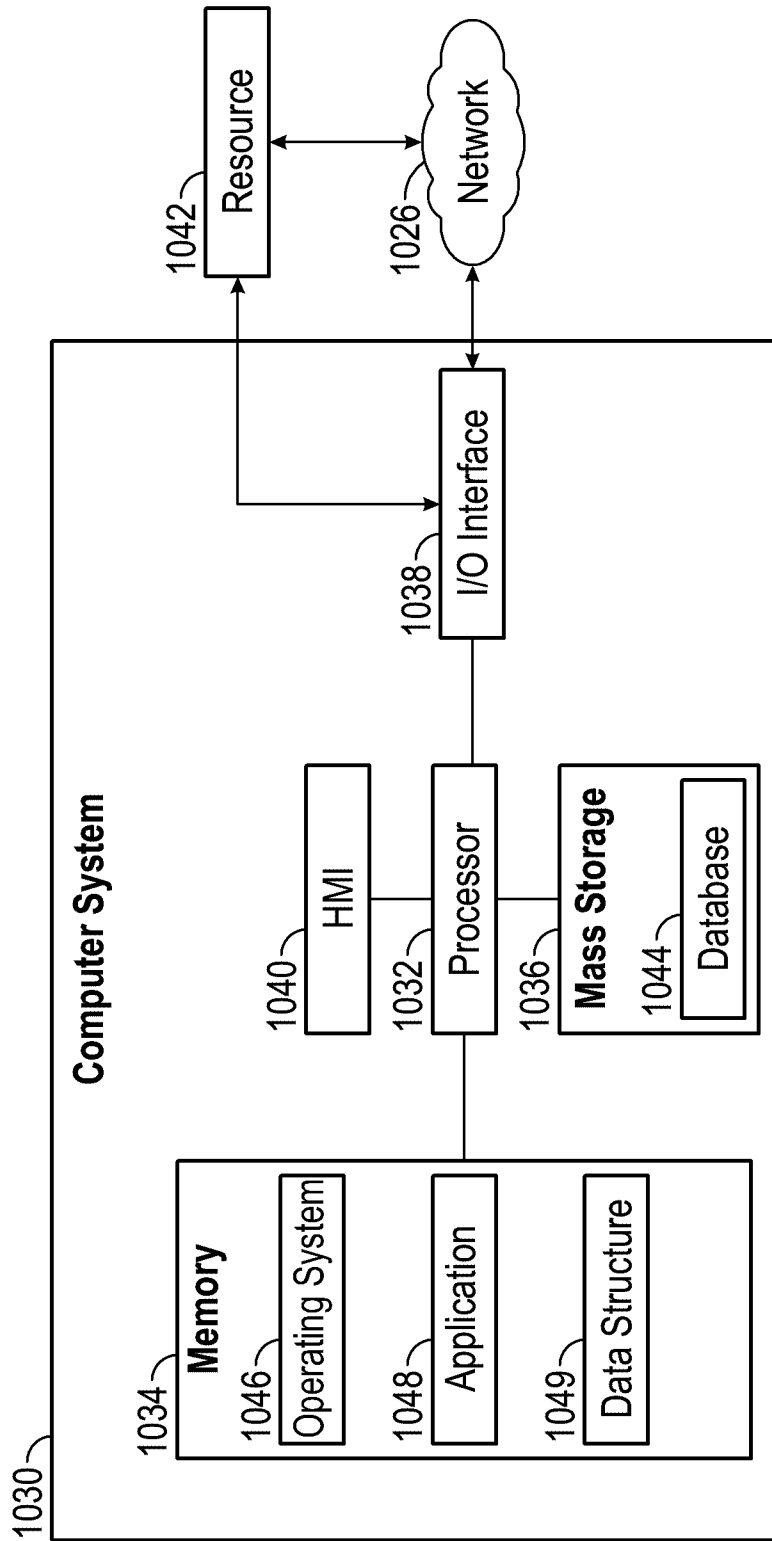


FIG. 5

