

- 1 -

REFUELING DEVICE

TECHNICAL FIELD

The presently disclosed subject matter relates to systems and methods for refueling an aircraft during flight.

BACKGROUND

5 Airborne refueling, also known as air refueling or in-flight refueling, refers to the process of transferring fuel from a tanker aircraft to a receiver aircraft during flight.

Two types of airborne refueling systems are:

- the hose and drogue system;
- the boom and receptacle or "flying boom" system.

10 In the hose and drogue system, the tanker aircraft is provided with one or more non-rigid refueling lines, at the end of each of which there is a drogue which functions as a stabilizer and includes a receptacle, while the receiver aircraft is fitted with a probe that is configured for engaging with the receptacle. In use, the drogue is not actively controlled, but rather aligns itself freely in the airflow aft of the tanker aircraft. The pilot
15 of the receiver aircraft controls the flight path thereof to ensure engaging contact between the probe and the receptacle. Thereafter, the receiver aircraft is refueled via the refueling line and probe.

 In the boom and receptacle system, the tanker aircraft includes a flying boom which is a rigid tube that telescopes outwardly and is gimbaled to the rear of the tanker
20 aircraft, and is otherwise retracted into the tanker fuselage when not in use. The boom carries a fuel line and includes a fuel transfer nozzle at the end thereof. Once the tanker aircraft and receiver aircraft are in close proximity and flying in formation, a dedicated operator in the tanker aircraft controls the position of the boom and inserts the end of the boom including the nozzle into a receptacle provided on an upper part of the
25 receiver aircraft, ensuring proper mating between the nozzle and receptacle, after which fuel transfer can begin.

- 2 -

In addition, there are some tanker aircraft that include a flying boom system and at least one hose and drogue system as well, and are commonly known as Multi-Point Refueling Systems (MPRS). In some cases a hose and drogue system is provided at the tail of the tanker aircraft, and thus only this system or the flying boom system can be
5 used at any one time. In other cases, two under-wing hose and drogue pods, known as Wing Air Refueling Pods (WARPs), can be provided, one under each wing, in addition to the flying boom system.

GENERAL DESCRIPTION

According to one aspect of the presently disclosed subject matter there is
10 provided a computerized method of controlling a refueling device, including:

(a) providing the refueling device that is attached by means of a non-rigid hose to a tanker aircraft; the refueling device having a refueling device body connected to a refueling nozzle by a joint, the joint facilitating at least a degree of freedom of the refueling device body relative to the refueling nozzle when the refueling nozzle is
15 engaged with a receptacle of a receiver aircraft, constituting an engaged state;

(b) repeatedly performing by a controller:

in an instance which the refueling device is not engaged with the receiver aircraft, constituting a non-engaged state:

(b1) receiving a first roll angle of the tanker aircraft from the
20 tanker aircraft;

(b2) determining a first desired roll angle of the refueling device based on the first roll angle of the tanker aircraft; and

(b3) providing a first one or more commands related to the first desired roll angle of the refueling device for controlling one or more roll
25 elements of the refueling device thereby attempting to achieve or maintain a first roll angle of the refueling device that is substantially the same as the first roll angle of the tanker aircraft; and

in an instance which the refueling device is engaged with the receiver aircraft in the engaged state:

30 (b4) receiving a second roll angle of the tanker aircraft from the tanker aircraft;

- 3 -

(b5) determining a second desired roll angle of the refueling device based on the second roll angle of the tanker aircraft; and

(b6) providing a second one or more commands related to the second desired roll angle of the refueling device for controlling one or more yaw elements of the refueling device thereby attempting to achieve or maintain a second roll angle of the refueling device that is substantially the same as the second roll angle of the tanker aircraft; wherein the second roll angle of the refueling device during the engaged state is facilitated at least due to the degree of freedom between the refueling device body and the refueling nozzle.

In addition to the above features, the method according to this aspect of the presently disclosed subject matter can include one or more of features (i) to (xiii) listed below, in any desired combination or permutation which is technically possible:

- (i). wherein stage (b3) further includes: providing a first one or more commands related to the first desired roll angle of the refueling device for controlling the one or more yaw elements of the refueling device; and wherein stage (b6) further includes: providing a second one or more commands related to the second desired roll angle of the refueling device for controlling the one or more roll elements of the refueling device; thereby providing one or more commands to both the one or more roll elements and the one or more yaw elements seamlessly, irrespective of whether the refueling device is in the non-engaged state or the engaged state.
- (ii). performing gain calibration to affect the first one or more commands and/or the second one or more commands provided to the one or more roll elements and/or the one or more yaw elements and thereby modify the effect that the one or more roll elements and/or the one or more yaw elements has when attempting to achieve the first and/or second desired roll angle.
- (iii). wherein stage (b2) further includes: receiving a first roll angle of the refueling device and determining a first difference between the first desired roll angle and the first roll angle of the refueling device and utilizing the first difference for providing the first one or more commands; and wherein stage (b5) further includes: receiving a second roll angle of the refueling device and determining a

- 4 -

second difference between the second desired roll angle and the second roll angle of the refueling device and utilizing the second difference for providing the second one or more commands.

- (iv). controlling the one or more roll elements and/or the one or more yaw elements based on the first and/or second one or more commands to attempt to achieve or maintain a roll angle of the refueling device that is substantially the same as the roll angle of the tanker aircraft.
- (v). wherein stage (b2) and/or stage (b5) further includes: obtaining a relative position of the tanker aircraft and the refueling device; obtaining a speed of the tanker aircraft; and determining a side speed of the refueling device relative to the tanker based on the relative position of the tanker aircraft and the refueling device and the speed of the tanker aircraft; wherein the side speed of the refueling device relative to the tanker is used to prevent or reduce oscillation of the refueling device and thereby help to achieve or maintain a roll angle of the refueling device that is substantially the same as the roll angle of the tanker aircraft.
- (vi). wherein stage (b2) and/or stage (b5) further includes obtaining a roll rate of the refueling device; wherein the roll rate is used to prevent or reduce oscillation of the refueling device and thereby help to achieve or maintain a roll angle of the refueling device that is substantially the same as the roll angle of the tanker aircraft.
- (vii). wherein the refueling device is an unmanned aerial vehicle (UAV).
- (viii). wherein the tanker aircraft is a UAV.
- (ix). wherein the receiver aircraft is a UAV.
- (x). wherein the joint is a spherical shaped joint.
- (xi). wherein the controller is a Proportional Integral (PI) controller.
- (xii). wherein the one or more roll elements are one or more ailerons.
- (xiii). wherein the wherein the one or more yaw elements are one or more rudders.

According to another aspect of the presently disclosed subject matter there is provided a non-transitory program storage device readable by machine, tangibly embodying a program of instructions executable by the machine to perform the above method of controlling a refueling device.

- 5 -

This aspect of the disclosed subject matter can optionally include one or more of features (i) to (xiii) listed above, *mutatis mutandis*, in any desired combination or permutation which is technically possible.

According to another aspect of the presently disclosed subject matter there is
5 provided an inflight refueling system, including:

a refueling device that is attached by means of a non-rigid hose to a tanker aircraft; the refueling device having a refueling device body connected to a refueling nozzle by a joint, the joint facilitating at least a degree of freedom of the refueling device body relative to the refueling nozzle when the refueling nozzle is engaged with a
10 receptacle of a receiver aircraft, constituting an engaged state;

a sensor configured to determine a roll angle of the tanker aircraft; and

a controller configured to repeatedly perform the following:

when the refueling device is not engaged with the receiver aircraft,
constituting a non-engaged state:

15 (1) receive a first roll angle of the tanker aircraft from the tanker aircraft;

(2) determine a first desired roll angle of the refueling device based on the first roll angle of the tanker aircraft; and

(3) provide a first one or more commands related to the first
20 desired roll angle of the refueling device to control one or more roll elements of the refueling device to thereby attempt to achieve or maintain a first roll angle of the refueling device that is substantially the same as the first roll angle of the tanker aircraft; and

when the refueling device is engaged with the receiver aircraft in the
25 engaged state:

(4) receive a second roll angle of the tanker aircraft from the tanker aircraft;

(5) determine a second desired roll angle of the refueling device based on the second roll angle of the tanker aircraft; and

30 (6) provide a second one or more commands related to the second desired roll angle of the refueling device to control one or

- 6 -

more yaw elements of the refueling device to thereby attempt to achieve or maintain a second roll angle of the refueling device that is substantially the same as the second roll angle of the tanker aircraft; wherein the second roll angle of the refueling device during the engaged state is facilitated at least due to the degree of freedom
5 between the refueling device body and the refueling nozzle.

This aspect of the disclosed subject matter can optionally include one or more of features (i) to (xiii) listed above, *mutatis mutandis*, in any desired combination or permutation which is technically possible.

10 BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it can be carried out in practice, examples will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Figs. 1 and 2 illustrate a tanker system with multiple refueling devices for
15 refueling aircraft during flight, in accordance with certain examples of the presently disclosed subject matter;

Fig. 3 illustrates a refueling device, in accordance with certain examples of the presently disclosed subject matter;

Fig. 4 illustrates a block diagram of a system including a controller for
20 controlling a roll angle of a refueling device, in accordance with certain examples of the presently disclosed subject matter;

Fig. 5 illustrates functional modules that are part of a controller for controlling a roll angle of a refueling device, in accordance with certain examples of the presently disclosed subject matter;

25 **Fig. 6** illustrates an implementation of a controller for controlling a roll angle of a refueling device, in accordance with certain examples of the presently disclosed subject matter;

Fig. 7 illustrates a flow chart of a method for controlling a refueling device, in accordance with certain examples of the presently disclosed subject matter;

- 7 -

Figs. 8 and 9 illustrate some of the forces that are present during various stages of the refueling process, in accordance with certain examples of the presently disclosed subject matter; and

Figs. 10 to 13 illustrate a refueling device during various stages of the refueling process, in accordance with certain examples of the presently disclosed subject matter.

DETAILED DESCRIPTION

In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those skilled in the art that the presently disclosed subject matter can be practiced without these specific details. In other instances, well-known methods, procedures, components and circuits have not been described in detail so as not to obscure the presently disclosed subject matter.

Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as, "providing", "performing", "receiving", "determining", "controlling", "obtaining", "calculating", "generating", or the like, refer to the action(s) and/or process(es) of a controller that manipulate and/or transform data into other data, the data represented as physical, such as electronic, quantities, and/or, the data representing the physical objects. The term "controller" should be expansively construed to cover any kind of hardware-based electronic device with data processing capabilities, for example, a computer, etc., and including, by way of non-limiting example, controller **400** including processing circuitry **500** (further detailed herein with regard to **Fig. 5**) and/or processing circuitry **600** (further detailed herein with regard to **Fig. 6**), according to some examples disclosed in the present application.

The operations in accordance with the teachings herein can be performed by a computer specially constructed for the desired purposes or by a general-purpose computer specially configured for the desired purpose by a computer program stored in a non-transitory computer-readable storage medium.

Examples of the presently disclosed subject matter are not described with reference to any particular programming language. It will be appreciated that a variety

- 8 -

of programming languages can be used to implement the teachings of the presently disclosed subject matter as described herein.

The term, "substantially", used herein includes variations that are equivalent for an intended purpose or function.

5 As will be further detailed with reference to **Fig. 5**, controller **400** can be configured to execute several functional modules in accordance with computer-readable instructions implemented on a non-transitory computer-readable storage medium. Such functional modules are referred to hereinafter as included in controller **400**.

It is noted that the teachings of the presently disclosed subject matter are not
10 bound by the structure described with reference to **Figs. 1 to 13**. Equivalent and/or modified structure can be consolidated or divided in another manner and can be implemented in any appropriate combination of software with firmware and/or hardware and executed on suitable device(s). For example, one or more elements described as being located on the refueling device can be located on the tanker aircraft
15 and vice versa. As another example, the functionality of one or more of the modules described in **Fig. 5** can be consolidated or divided such that a single module takes the place of multiple modules and vice versa.

It is also noted that the teachings of the presently disclosed subject matter are not bound by the flow chart illustrated in **Fig. 7**; the illustrated operations can occur out
20 of the illustrated order. For example, **(block 704) to (block 712)** which are shown as being executed substantially concurrently can be executed in succession. It is also noted that whilst the flow chart in **Fig. 7** is described with reference to elements of controller **400**, e.g., including processing circuitry **500** and/or processing circuitry **600**, this is by no means binding, and the operations can be performed by elements other than
25 those described herein.

Figs. 1 and 2 illustrate a tanker system **100** which can include a tanker aircraft **112** with multiple in-flight refueling systems **150**, according to one example of the presently disclosed subject matter.

In this example, tanker aircraft **112** has three such in-flight refueling systems **150**,
30 one on each one of the port wing **114** and starboard wing **116**, and a third one on the rear

- 9 -

portion of fuselage 115. Tanker aircraft 112 can be configured for in-flight concurrent refueling of one or more receiver aircraft 220 via a fuel receptacle 222. In some examples, tanker aircraft 112 can have more or less in-flight refueling systems 150, arranged in any suitable configuration with respect to tanker aircraft 112.

5 By way of non-limiting example, tanker aircraft 112 can be a suitably equipped Boeing 767 and each receiver aircraft 220 can include any one of suitably equipped F-15, or F-16, or B2 stealth bomber, or other suitably equipped fighter, bomber or other aircraft. In some examples, tanker aircraft 112 can be an unmanned aerial vehicle (UAV), and/or, at least one of receiver aircraft 220 can be a UAV.

10 Each in-flight refueling system 150 can include an elongate, non-rigid, fuel delivery hose 152, reversibly extendible from tanker aircraft 112. A first end (not shown) of hose 152 can be connected to a refueling fuel tank (not shown) carried by tanker aircraft 112. For example, such a refueling fuel tank can be an internal fuel tank of tanker aircraft 112, (e.g., the tanker aircraft's own fuel tanks, a special fuel reservoir mounted
15 internally in tanker aircraft 112, etc.), or, an external fuel tank (e.g., fuel pods, etc.).

Hose 152 can be flexible and can be retracted into a roll up drum (not shown), suitably provided in tanker aircraft 112, and selectively deployed therefrom when required.

The second (aft) end 154 of hose 152 can be operatively connected to a respective refueling device 300 that can be towed in a forward direction A by tanker
20 aircraft 112 via hose 152 when hose 152 is extended and tanker aircraft 112 is in flight. Refueling device 300 includes a boom member 330 and a fuel delivery nozzle 335 in fluid communication with hose 152 (see Fig. 2, for example), which are described in greater detail below with reference to Fig. 3. In some examples, refueling device 300 can be a UAV.

25 In this example, one in-flight refueling system 150 is centrally-located and mounted with respect to the rear fuselage 115 of tanker aircraft 112, and each of the other two in-flight refueling systems 150 is included in a respective pod 151 that is attached to the underside of the respective wing 114, 116 (see Fig. 2, for example).

- 10 -

Fig. 3 illustrates a refueling device **300** for use with an in-flight refueling system, for example at least one of the in-flight refueling systems **150** illustrated in **Figs. 1 and 2**, according to an example of the presently disclosed subject matter.

For convenience, roll axis **R**, pitch axis **P**, and yaw axis **Y** can be conventionally defined with respect to refueling device **300**. Roll axis **R** is parallel to or co-axial with a longitudinal axis **311** of refueling device **300**. Pitch axis **P** is generally in lateral and orthogonal relationship to roll axis **R** (i.e., parallel to the horizontal when the body is at a zero roll angle). Yaw axis **Y** is in orthogonal relationship to roll axis **R** and pitch axis **P** (i.e., parallel to the vertical when the body is at a zero pitch angle).

Refueling device **300** can be affixed to the end **154** of hose **152** and includes body **310**. Body **310** can include a boom member **330** in fluid communication with hose **152**. Boom member **330** can define a boom axis **331** and can include a fuel delivery nozzle **335** at a terminus of boom member **330**. Nozzle **335** can be configured for reversibly engaging with fuel receptacle **222** of receiver aircraft **220**.

Refueling device **300**, in particular boom member **330** and nozzle **335**, can be sized to allow suitable fuel flow rates for refueling a wide range of receiver aircraft.

Boom member **330** includes a joint **340** on boom axis **331**. Joint **340** can be configured for allowing relative movement between body **310** and nozzle **335**, especially while nozzle **335** is engaged with fuel receptacle **222**. In this example, joint **340** is in the form of a spherical-shaped ball joint, and is configured for allowing relative movement between body **310** and nozzle **335**, and by extension receiver aircraft **220** when engaged, in at least one degree of freedom.

In some examples, nozzle **335** being engaged with fuel receptacle **222** can define an engaged state of refueling device **300**, whereas nozzle **335** not being engaged with fuel receptacle **222** can define a non-engaged state of refueling device **300**. In some examples, refueling device **300** being in an instance of an engaged state or being in an instance of a non-engaged state can be determined based on engagement state data, which is obtained using one or more engagement/disengagement sensor(s) **406**, described in greater detail below with reference to **Fig. 4**.

- 11 -

Boom member **330** can be pivotably mounted to body **310** about a pivot axis generally parallel to pitch axis **P** of body **310** at pivot joint **319**, and reversibly pivotable between a stowed or retracted position and a deployed position. In the stowed or retracted position, boom member **330** can be pivoted about the pivot axis into a position where the
5 terminus is closest to the underside of body **310**. In this position, boom axis **331** can be generally parallel to and displaced away from longitudinal axis **311** in a downward direction with respect to body **310**. In the deployed position illustrated in **Fig. 3**, boom member **330** can be variably pivoted about the pivot axis in a downward direction to provide a non-zero angular displacement, angle θ , between boom axis **331** and longitudinal
10 axis **311**. In this example, angle θ is in pitch with respect to refueling device **300**. Boom member **330** can be in the deployed position, at least, during in-flight refueling operation of refueling device **300**.

Refueling device **300** further includes one or more roll elements and one or more yaw elements configured to help control a spatial disposition of refueling device **300** when
15 towed aft of tanker aircraft **112** via hose **152**. The terms "roll elements" and "yaw elements" used herein refer to any appropriate device or mechanism for affecting the roll and yaw of the refueling device, respectively. For example, roll elements can be one or more control surfaces, such as ailerons, an air powered roll element, such as an air blower, and/or any other appropriate device or mechanism that is configured to rotate the refueling
20 device about its roll axis. Similarly, for example, yaw elements can be one or more control surfaces, such as rudders, an air powered yaw element, such as an air blower, and/or any other appropriate device or mechanism that is configured to rotate the refueling device about its yaw axis.

In this example, the one or more roll elements and the one or more yaw elements
25 are control surfaces, including ailerons **420** as roll elements and rudders **422** as yaw elements. In this example, ailerons **420** are a selectively controllable aerodynamic set of ailerons **420** that are pivotably mounted to an aileron arm of body **310** at an aft portion thereof. Rudders **422** are a selectively controllable set of aerodynamic rudders **422** that are pivotably mounted to rudder arms of body **310** at an aft portion thereof and orthogonal to
30 ailerons **420**.

- 12 -

Ailerons **420** and rudders **422** help enable refueling device **300** to be steered and/or to adopt a desired spatial disposition while being towed at the end **154** of hose **152**. In particular, ailerons **420** and rudders **422** can be controlled to affect the roll angle of refueling device **300**. Exemplary operation of ailerons **420** and rudders **422** is
5 described in greater detail below with reference to **Figs. 8 and 9**.

The term roll angle or bank angle is the angle at which the aircraft is rotated or inclined about its longitudinal axis with respect to the horizontal. For example, when the aircraft performs a roll, or a banked turn to change direction, the roll angle of the aircraft is affected.

10 Refueling device **300** can further include controller **400**, and, one or more refueling device sensor(s) **404**, which are described in greater detail below with reference to **Fig. 4**.

Fig. 4 illustrates a block diagram of a system including a controller **400** for controlling the roll angle of refueling device **300** during the in-flight refueling process,
15 in accordance with certain examples of the presently disclosed subject matter.

In this example, controller **400** is part of a system **401** which includes refueling device **300** and one or more tanker sensor(s) **450**.

Controller **400** can include processing circuitry (e.g. **500**, **600**, described below) including one or more memory, and one or more processors configured to execute
20 various operations as disclosed herein. Controller **400** may in some examples include a PID controller or PI controller, a microprocessor, a microcontroller or any other computing device or module or system. One implementation of controller **400** including a PID controller is described in greater detail below with reference to **Fig. 6**.

Controller **400** can, for example, be implemented as software in a computer
25 processor, as hardware, firmware, or as any combination thereof, executed on a suitable device or devices, that performs the functions as explained herein.

Controller **400** may include a plurality of controllers, possibly in a distributed architecture, which are adapted to independently and/or cooperatively operate to process various data, electrical and/or mechanical inputs (after being converted into electrical or
30 possibly digital form), for controlling the relevant components of system **401**, and for

- 13 -

enabling operations related to components of system **401**. In some cases multiple instances of controller **400**, or of a particular component or module within it, may be utilized for reasons of redundancy and availability.

Controller **400** can be operatively connected to one or more refueling device
5 sensor(s) **404**, one or more tanker sensor(s) **450**, one or more engagement/disengagement sensor(s) **406**, one or more aileron actuator(s) **410**, and one or more rudder actuator(s) **412**.

Controller **400** can be configured to receive data from the various one or more sensor(s) **404**, **406**, **450**. Controller **400** can also be configured to provide commands to
10 actuators **410**, **412**.

In this example, tanker sensor(s) **450** are located on-board tanker aircraft **112**, and are configured to determine a roll angle of tanker aircraft **112**. Tanker sensor(s) **450** can also be configured to determine, at least, one or more of the following: a position, speed, and/or acceleration of tanker aircraft **112**, etc. Data from tanker sensor(s) **450** can
15 be transmitted wirelessly to controller **400**. For example, tanker sensor(s) **450** can include a Micro-Electro-Mechanical Systems (MEMS) sensor (e.g., a MEMS vertical gyroscope, and/or, MEMS rate gyroscope), an accelerometer, a global positioning system (GPS), an inertial navigation system (INS), camera, Light Detection And Ranging (LIDAR) etc.

20 In this example, refueling device sensor(s) **404** are located on-board body **310** of refueling device **300**, and are configured to determine a roll angle of refueling device **300**. Refueling device sensor(s) **404** can also be configured to determine, at least, one or more of the following: a position, speed, and/or acceleration of refueling device **300**, a roll rate of refueling device **300**, etc. For example, refueling device sensor(s) **404**
25 can include a MEMS sensor (e.g., a MEMS vertical gyroscope, and/or, MEMS rate gyroscope), an accelerometer, GPS, INS, camera, LIDAR, etc.

In this example, engagement/disengagement sensor(s) **406** are located on-board body **310** of refueling device **300**, and, are configured to determine if refueling device **300** is engaged with receiver aircraft **220**. For example,
30 engagement/disengagement sensor(s) **406** can include proximity sensor(s), etc.

- 14 -

In this example, aileron actuator(s) **410** and rudder actuator(s) **412**, are located on-board body **310** of refueling device **300**. Actuators **410**, **412**, are operatively connected to ailerons **420** and rudders **422**, respectively. Actuators **410**, **412**, are configured to actuate the operation of ailerons **420**, and rudders **422**, respectively, and
5 control the angular position of their respective control surfaces **420**, **422** about their respective pivot axes.

Controller **400** can be configured to execute several functional modules in accordance with computer-readable instructions implemented on a non-transitory computer-readable storage medium. Such functional modules are referred to hereinafter
10 as included in controller **400**, and are described in greater detail below with reference to Fig. 5.

Fig. 5 illustrates a controller **400** including processing circuitry **500**, in accordance with certain examples of the presently disclosed subject matter. In this example, processing circuitry **500** includes functional modules that are part of
15 controller **400** for controlling a roll angle of a refueling device.

In this example, processing circuitry **500** includes sensor control module **502**, side speed determination module **504**, roll angle control module **506**, maneuvering/steering control module **508**, safety module **510**, engagement/disengagement control module **512**, and external data interface
20 module **514**.

Sensor control module **502** can be configured to operate one or more sensor(s) **404**, **406** in order to acquire data, and enables repeated determination of data, such as the roll angle of refueling device **300**, and engagement of refueling device **300** to receiver aircraft **220**, respectively.

Side speed determination module **504** can be configured to calculate a relative side speed of the refueling device relative to the tanker aircraft. In some examples, in order to calculate the side speed of the refueling device relative to the tanker aircraft, side speed determination module **504** can perform a differential function on an obtained position of tanker aircraft **112** and a differential function on an obtained position of
30 refueling device **300**, and then subtract the results from each other in order to determine the relative side speed. In some examples, in order to calculate the side speed of the

- 15 -

refueling device relative to the tanker aircraft, side speed determination module **504** can perform an integral function on an obtained acceleration of tanker aircraft **112** and an integral function on an obtained acceleration of refueling device **300**, and then subtract the results from each other in order to determine the relative side speed.

5 Roll angle control module **506** can be configured to calculate and provide roll control commands to actuators **410**, **412**, for controlling the roll angle of refueling device **300**, e.g., so that it is substantially the same as a roll angle of tanker aircraft **112**. The roll control commands can be used for controlling ailerons **420**, and/or, rudders **422**. Exemplary operation of roll angle control module **506** is described in
10 greater detail below with reference to **Fig. 7**.

Maneuvering/steering control module **508** can be configured to calculate and provide maneuvering/steering commands for maneuvering and steering refueling device **300**, e.g., to an engagement area and/or to perform engagement/disengagement. Maneuvering/steering control module **508** can be configured for enabling refueling
15 device **300** to be steered in three degrees of freedom: laterally (left and right), vertically (up and down), and longitudinally (forwards and backwards). Thus, maneuvering/steering control module **508** can be configured for providing one or more of: sideslip, up/down translation, forward-aft translation, relative to tanker aircraft **112**, and/or, to receiver aircraft **220**.

20 Safety module **510** can be configured to monitor hazardous situations in the refueling process. The hazardous situations can be defined by a set of thresholds and/or parameters and respective safety conditions. For example, safety module **510** can be configured to monitor that refueling device **300** does not approach receiver aircraft **220** (or vice versa) in an unsafe manner, and/or that refueling device **300** does not approach
25 tanker aircraft **112** (or vice versa) in an unsafe manner, etc.

Engagement/disengagement control module **512** can be configured to provide an engagement command to refueling device **300** for causing refueling device **300** to engage with fuel receptacle **222** of receiver aircraft **220** for performing refueling, and to provide a disengagement command to refueling device **300** to disengage from fuel
30 receptacle **222** of receiver aircraft **220**. According to examples of the presently disclosed subject matter, engagement/disengagement control module **512** can operate

- 16 -

responsive to an indication that receiver aircraft 220 is positioned in an engagement area. Exemplary operation of engagement/disengagement control module 512 is described in greater detail below with reference to Figs. 10-13.

External data interface module 514 can be configured to enable one or more
5 components of controller 400 to operate in cooperation with auxiliary units, devices, data stores, systems or modules. For example, external data interface module 514 can implement various protocols, software languages, drive signals, etc. Further, by way of example, external data interface module 514 can be used to operate certain auxiliary units, devices, data stores, systems or modules on board one or more of refueling
10 device 300, receiver aircraft 220, or tanker aircraft 112, such as tanker sensor(s) 450.

Fig. 6 illustrates an implementation of controller 400 including processing circuitry 600, in accordance with certain examples of the presently disclosed subject matter.

As mentioned above, controller 400 can be a hardware processor running
15 software. Controller 400 can be hardware implementing at least some of the operations described below with reference to the method of Fig. 7.

In this example, processing circuitry 600 includes an input logic module 602, a PID controller module 604, and an output logic module 606.

Input logic module 602 can include a summing point 648 for calculating a
20 difference between a roll angle of the tanker and a roll angle of the refueling device.

PID controller module 604 can be, or include, a proportional-integral-derivative (PID) controller or a proportional-integral (PI) controller. A proportional-integral controller (PI Controller) is a case of a proportional-integral-derivative controller (PID controller) in which the derivative (D) of the error is not used. The lack of derivative
25 action can make the system more steady in the steady state in the case of noisy data, because derivative action can be more sensitive to higher-frequency terms in the inputs. The output of input logic module 602 can be input to PID controller module 604.

Output logic module 606 can include a summing point 612, and a plurality of gains 618, 620, 636, 638. Output logic module 606 can be configured to generate
30 commands 632, 634 that are used to control operation of one or more ailerons and one

- 17 -

or more rudders. The output of PID controller module **604** can be input to output logic module **606** and added to additional weights or gains at summing point **612**.

The output of controller **400** can be input to plant/process **640**.

For example, when controller **400** is/includes a PI controller, the obtained
5 refueling device roll angle can be the process variable, and the desired roll angle which
can be the obtained tanker roll angle can be the setpoint. The roll control commands to
the actuators are the manipulated/control variable which is the output from controller
400 and the input to the process or plant **640**. The difference between the present roll
angle of the refueling device and the setpoint (tanker roll angle) can be the error. By
10 measuring the refueling device roll angle and subtracting it from the setpoint (tanker roll
angle), the error can be found. Based on the error, controller **400** calculates how much
to adjust the ailerons and/or rudders to affect the refueling device roll angle, i.e., what
roll control commands to provide to the ailerons and/or rudders. The feedback of the
process or plant can be the obtained updated roll angle of the refueling device, which
15 can then be used to further control the roll angle of the refueling device in an attempt to
achieve the desired roll angle, one that is substantially the same as the tanker roll angle.

In this example, proportional action adjusts the ailerons and/or rudders in
proportion to the existing error. Integral action can use the accumulated state error, from
the past, to detect whether the desired roll angle of the refueling device is settling out
20 and to adjust the ailerons and/or rudders in relation not only to the error but also the
time for which it has persisted. In some examples the formulation of integral action can
be to adjust the ailerons and/or rudders in small persistent steps that are proportional to
the current error. Over time, the steps accumulate and add up, dependent on past errors.

The operation of controller **400** is described in further detail below with
25 reference to **Fig. 7**.

Fig. 7 illustrates a flow chart of a method **700** for controlling a refueling device
during in-flight refueling, in accordance with certain examples of the presently
disclosed subject matter.

Method **700** can be performed throughout the refueling process, while refueling
30 device is in a non-engaged state or in an engaged state.

- 18 -

Method **700** includes the preliminary step of obtaining roll control data (**block 702**) (e.g., determined by the various sensors and obtained by sensor control module **502**, and/or, external data interface module **514** of controller **400**). Obtaining roll control data (**block 702**) includes obtaining a roll angle of the tanker aircraft
5 (**block 704**) (e.g., determined by tanker sensor(s) **450**) and obtaining a roll angle of the refueling device (**block 706**) (e.g., determined by refueling device sensor(s) **404**).

Obtaining roll control data (**block 702**) can also optionally include obtaining a roll rate of the refueling device (**block 708**) (e.g., determined by refueling device sensor(s) **404**), obtaining a side speed of the refueling device relative to the tanker
10 aircraft (**block 710**) (e.g., calculated by side speed determination module **504**), and obtaining engagement state data (**block 712**) (e.g., determined by engagement/disengagement sensor(s) **406**).

Upon obtaining roll control data (**block 702**) the difference between the roll angle of the tanker aircraft and the roll angle of the refueling device is determined
15 (**block 714**) (e.g., calculated by roll angle control module **506**, and/or, input logic module **602** of controller **400**).

Upon determining the difference between the roll angle of the tanker aircraft and the roll angle of the refueling device (**block 714**) a roll correction command is generated (**block 716**) (e.g., calculated by roll angle control module **506**, and/or, PID
20 controller module **604** of controller **400**). The roll correction command can be generated based on the determined difference between the roll angle of the tanker aircraft and the roll angle of the refueling device.

Optionally, upon generating the roll correction command (**block 716**) the roll correction command can be adjusted (**block 718**) (e.g., by roll angle control module **506**
25 and/or, output logic module **606** of controller **400**). The roll correction command can be adjusted based on the obtained roll rate of the refueling device, the obtained side speed of the refueling device relative to the tanker aircraft, and/or, the engagement state data. In some examples, the roll correction command can be adjusted based on an adjusted roll rate of the refueling device, and/or, an adjusted side speed of the refueling device
30 relative to the tanker aircraft. In some examples, the roll correction command, the roll

- 19 -

rate, and/or, the side speed of the refueling device relative to the tanker aircraft can be adjusted by using gains, as described in greater detail below with reference to **Fig. 6**.

Upon generating/adjusting the roll correction command (**block 716/block 718**) one or more roll control commands, to be used by the refueling device to attempt to
5 achieve or maintain a roll angle that is substantially the same as the roll angle of the tanker aircraft, are generated (**block 720**) (e.g., by roll angle control module **506**, and/or, output logic module **606** of controller **400**). The roll control commands can be generated based on the generated/adjusted roll correction command.

Generating roll control commands for the refueling device (**block 720**) can
10 include generating one or more aileron control commands for controlling one or more of the refueling device ailerons (**block 722**), and/or generating one or more rudder control commands for controlling one or more of the refueling device rudders (**block 724**). Generating an aileron command, and/or a rudder command can be done by splitting, and/or adjusting a roll control command, e.g., using gains as described in greater detail
15 below with reference to **Fig. 6**.

In some examples it might take more than one iteration of the process for the roll angle of the refueling device to achieve the desired roll angle. In some examples, controller **400** is configured to operate in a continuous manner so that it is constantly using the feedback from the system to attempt to achieve or maintain a desired roll
20 angle (based on a calculated error).

In some examples, certain steps and not others can be performed in iteration. For example, a previously determined roll angle of the tanker aircraft and a newly determined updated roll angle of the refueling device can be used to improve on a previous attempt to reach the previously determined desired roll angle, without
25 determining a new roll angle of the tanker aircraft, i.e., performing one or more iterations of the operations of (**block 706**), (**block 714**), and (**block 716**) based on a previously obtained roll angle of the tanker aircraft, before performing the operation of (**block 704**) again.

In some examples, a roll angle of the tanker aircraft that was obtained during an
30 engaged state can be used to determine the desired roll angle of the refueling device in a non-engaged state, and vice versa.

- 20 -

An exemplary operation of controller **400** is described, as follows, with reference to **Figs. 6 and 7**. It is also noted that whilst the operation of controller **400** is described with reference to operations of control method **700** and elements of system **401**, this is by no means binding, and the operation of controller **400** can be performed by using operations and elements other than those described herein.

Referring to **Figs. 6 and 7**, a determined difference between a roll angle of the tanker and a roll angle of the refueling device ($\Delta\phi = \phi_t - \phi_d$) **608** can be provided as input to PID controller module **604** (e.g., from input logic module **602**).

Although in the description above the difference between the roll angle of the tanker and the roll angle of the refueling device ($\Delta\phi$) is described as being determined (**block 714**) as a result of obtaining the roll angle of the tanker aircraft (**block 704**) and obtaining the roll angle of the refueling device (**block 706**) and calculating the difference, in some examples if the difference between the roll angles ($\Delta\phi$) is determined in another manner, then that difference ($\Delta\phi$) can also be used by controller **400**.

The output of PID controller module **604** can be one or more roll correction command(s) **610** for controlling the operation of one or more ailerons **420** and/or one or more rudders **422** of refueling device **300** (e.g., as generated in (**block 716**)).

In some examples, PID controller module **604** has internal gains (not shown), and the output **610** of PID controller module **604** can be affected by these internal gains.

Optionally, the output **610** of PID controller module **604** can be provided to a summing point **612** (e.g., of output logic module **606**) where the determined roll rate of the refueling device (**P**) **614** (e.g., obtained in (**block 708**)) and/or the determined side speed of the refueling device relative to the tanker aircraft ΔV_y **616** (e.g., obtained in (**block 710**)) are added to the output of PID controller module **604** to adjust the one or more roll correction command(s) **610** and produce one or more adjusted roll correction command(s) **630** (e.g., as adjusted in (**block 718**)).

Although in the description above the side speed of the refueling device relative to the tanker aircraft ΔV_y **616** is described as being calculated by side speed determination module **504** (**block 710**), in some examples if the side speed of the

- 21 -

refueling device relative to the tanker aircraft ΔV_y 616 is obtained or determined in another manner, then that ΔV_y 616 can also be used by PID controller module 604.

In some examples, the determined roll rate of the refueling device (P) 614, and/or the side speed of the refueling device relative to the tanker aircraft ΔV_y 616 can be provided to gains 618, 620, respectively, for adjustment, before being provided to summing point 612.

Using the determined roll rate of the refueling device (P) 614, and/or the determined side speed of the refueling device relative to the tanker aircraft ΔV_y 616, can help prevent or reduce oscillation of the system and help the system to reach a steady state more quickly, and thereby help to achieve or maintain a roll angle of the refueling device that is substantially the same as the roll angle of the tanker aircraft.

The roll correction command(s) 610, or adjusted roll correction command(s) 630, are used to generate one or more roll control command(s), 632, 634 (e.g., as generated in (block 720)).

In some examples, roll control commands 632, 634 are generated by splitting the roll correction command(s) 610, or 630, into aileron roll control command(s) δ_a 632 and rudder control command(s) δ_r 634 (e.g., as generated in (block 722) and (block 724)).

In some examples, roll control commands 632, 634 can be the same command for both ailerons 420 and rudders 422. An example of the roll control commands being the same for both is described in greater detail below with reference to Figs. 8 and 9.

In some examples, gain calibration can be performed using gains 636, 638, to affect roll control commands 632, 634, respectively, and thereby modify the effect that ailerons 420 and/or rudders 422 have when attempting to achieve the desired roll angle. For example, gain calibration can be done to adjust the size of the gains in order to stabilize the system and make the system more robust to disturbances.

In some examples, gain calibration can be performed based on engagement state data 652 (e.g., as obtained in (block 712)) which is indicative of an engagement state of the refueling device, e.g., determined by engagement/disengagement sensor(s) 406.

- 22 -

Gain calibration can affect the value of one or more of gains **618**, **620**, **636**, **638**, and/or, the internal gains of PID controller module **604**. For example, upon engagement, and/or disengagement, certain gains can be faded in, and/or, faded out, to prevent jumps and disturbances to the system.

5 In some examples, gain scheduling can be performed. Gain scheduling can affect the value of one or more of gains **618**, **620**, **636**, **638**, and/or the internal gains of PID controller module **604** as a result of one or more determined conditions. For example, gain scheduling can depend on one or more of: a determined height of the refueling device, a determined speed of the refueling device, a determined engagement
10 of the refueling device, etc.

In some examples, roll control commands **632**, **634** can be provided to both ailerons **420** and rudders **422** seamlessly throughout the refueling process, while refueling device **300** is in both engagement states, i.e., both the non-engaged state and the engaged state. Providing roll control commands **632**, **634** to both ailerons **420** and
15 rudders **422** throughout the refueling process can prevent any jumps or disturbances that might occur from switching modes of operation, e.g., which would be done upon engagement or disengagement. Roll control commands **632**, **634** can be provided to both ailerons **420** and rudders **422** throughout the process since the effect of ailerons **420** on the roll angle is dominant in the non-engaged state, and the effect of
20 rudders **422** on the roll angle is dominant in the engaged state. An example of the roll control commands being provided to both the ailerons and the rudders seamlessly throughout the refueling process is described in greater detail below with reference to **Figs. 8 and 9**.

In some examples, a switch (not shown) can be provided for switching between
25 modes of operation, depending upon engagement of the refueling device. In such examples, the switch can be operated based on obtained engagement state data **652**, e.g., determined by engagement/disengagement sensor(s) **406**. For example, in an engaged state, only rudder roll control command(s) **634** are provided to rudders **422**, and, roll control commands are not provided to ailerons **420**. In a non-engaged state, only aileron
30 roll control commands **632** are provided to ailerons **420**, and roll control commands are not provided to rudders **422**.

- 23 -

In some examples, aileron roll control command(s) **632** can be provided to aileron actuator(s) **410** and rudder roll control command(s) **634** can be provided to rudder actuator(s) **412**.

In some examples, aileron actuator(s) **410** and rudder actuator(s) **412** are part of
5 plant **640**.

Plant **640** may refer to the characteristics and dynamics of all of, or some of, the particular refueling device, actuators, ailerons, rudders, etc. The dynamics of these particular systems may drive how plant **640** behaves and responds to the command(s). As the ailerons **420** and/or rudders **422** that are attached to refueling device **300** are
10 adjusted, this can affect the roll angle of refueling device **300** relative to the roll angle of tanker aircraft **112**. The result of plant **640** may be a movement of refueling device **300**, thereby affecting the roll angle of refueling device **300** relative to the roll angle of tanker aircraft **112**, and thus a changed value of the difference between the tanker roll angle and the refueling device roll angle.

15 Gain coefficients for controller **400** may be determined and tuned for each "plant", e.g. for each particular combination of types of refueling devices, hoses, tanker aircraft and receiver aircraft, or their components (e.g., rudders and ailerons). In some embodiments, the coefficient values for each combination of systems may be stored in a data store, and relevant values can be provided and used, depending on the different
20 refueling situations.

The feedback from plant **640** can include an obtained refueling device roll angle ϕ_d **646**. Refueling device roll angle ϕ_d **646** can be provided to input logic module **602**, e.g. summing point **648**. An obtained tanker roll angle ϕ_t **650** can also be provided to input logic module **602**, e.g. summing point **648**, and, the result can be the determined
25 difference between the roll angle of the tanker and the roll angle of the refueling device $\Delta\phi$ **608**, which can be provided as input to PID controller module **604**.

The feedback from plant **640** can also optionally include a determined roll rate of the refueling device (**P**) **614**, which can be provided to output logic module **606**, e.g., summing point **612**, as described above.

- 24 -

Figs. 8 and 9 illustrate some of the forces that are present during various stages of the refueling process, in accordance with certain examples of the presently disclosed subject matter.

In **Fig. 8**, refueling device **300** is in a non-engaged state and roll control
5 commands **632, 634** are used to control ailerons **420** and rudders **422**. Using aileron roll control command(s) **632** to actuate ailerons **420** generates aileron forces **813**. As a result, aileron forces **813** together with aileron arm **815** generate free state rolling movement **816** about free state roll pivot point **814**, which affects the roll angle of refueling device **300**. In this case, even if rudder roll control command(s) **634** are
10 provided to actuate rudders **422** and generate rudder forces **812**, since refueling device **300** is in a non-engaged state and is free to rotate about pivot point **814** (since nozzle **335** is not constrained), rudder forces **812** are relatively insignificant in comparison to aileron forces **813** for affecting the rolling movement of refueling device **300**, i.e., the refueling device roll angle.

15 In **Fig. 9**, refueling device **300** is in an engaged state and roll control commands **632, 634** are used to control rudders **422** and ailerons **420**. Using rudder roll control command(s) **634** to actuate rudders **422** generates rudder forces **912**. As a result, rudder forces **912** together with boom member **330** generate engaged state rolling movement **919** about joint **340**, which acts as an engaged state roll pivot point. In this
20 case, even if aileron roll control command(s) **632** are provided to actuate ailerons **420** and generate aileron forces **913**, since refueling device **300** is in an engaged state and is not free to rotate about pivot point **814** (since nozzle **335** is constrained), aileron forces **913** are relatively insignificant in comparison to rudder forces **912** for affecting the rolling movement of refueling device **300**, i.e., the refueling device roll angle. When
25 refueling device **300** is in an engaged state, the constraint on nozzle **335** causes engaged state constraint side force **920**. Engaged state constraint side force **920** together with boom member **330** neutralize rolling movement **816** about pivot **814** that occurs when refueling device **300** is in a disengaged state (see **Fig. 8**, for example).

Providing roll control commands **632, 634** to both ailerons **420** and rudders **422**
30 seamlessly throughout the refueling process without switching can reduce the

- 25 -

complexity of control needed to achieve some of the goals during the refueling process. Some of these goals are described in greater below with reference to **Figs. 10 to 13**.

Figs. 10 to 13 illustrate a refueling device **300** during various stages of the refueling process, in accordance with certain examples of the presently disclosed
5 subject matter.

Fig. 10 illustrates refueling device **300** in a non-engaged state before it has reached engagement area **1000**. In this example, the goals are for refueling device **300** and receiver aircraft to be in their respective proper positions in engagement area **1000** to enable engagement between nozzle **335** and fuel receptacle **222**, and to then perform a safe
10 refueling and disengagement. In order to facilitate these goals, controller **400** will attempt to maintain a roll angle of refueling device **300** that is substantially the same as tanker aircraft **112** throughout the process.

For example, maintaining the desired roll angle can be facilitated by roll angle control module **506** of controller **400**.

Fig. 11 illustrates refueling device **300** in parallel alignment with tanker aircraft **112** and receiver aircraft **220**, with all three being in parallel alignment with the horizon of the Earth. **Fig. 12** illustrates refueling device **300** in parallel alignment with tanker aircraft **112** and receiver aircraft **220**, with all three being in rotation relative to the horizon of the Earth. Maintaining a roll angle of refueling device **300** that is substantially
20 the same as the roll angle of tanker aircraft **112** allows the parallel alignment shown in **Fig. 11** to be maintained despite the turning of tanker aircraft **112**. Maintaining this parallel alignment throughout the buildup to the engagement allows the position of nozzle **335** to be adjusted relative to fuel receptacle **222** without having to rotate nozzle **335** relative to the position of fuel receptacle **222**. This can simplify the process of aligning and engaging
25 nozzle **335** to fuel receptacle **222**, and prevent potential danger to the pilot of receiver aircraft **220**, thereby facilitating the above-stated goals.

For example, the aligning of nozzle **335** with fuel receptacle **222** can be facilitated by maneuvering/steering control module **508** of controller **400**.

When boom member **330** and nozzle **335** are in a predetermined spatial disposition
30 with respect to fuel receptacle **222** (i.e., at the engagement area **1000** of **Fig. 10**),

- 26 -

engagement between nozzle 335 and fuel receptacle 222 can be performed to enable the refueling of receiver aircraft 220. For example, refueling device 300 can be moved towards receiver aircraft 220 to effect engagement between nozzle 335 and fuel receptacle 222.

For example, the engagement can be facilitated by engagement/disengagement
5 control module 512 of controller 400.

Fig. 13 illustrates refueling device 300 in an engaged state. Once nozzle 335 is engaged with fuel receptacle 222 of receiver aircraft 220, tanker aircraft 112 can begin refueling receiver aircraft 220. Maintaining a roll angle of refueling device 300 that is substantially the same as the roll angle of tanker aircraft 112 during refueling prevents
10 potential danger to the pilot of receiver aircraft 220, thereby facilitating the above-stated goals.

As mentioned above, maintaining the desired roll angle can be facilitated by roll angle control module 506 of controller 400.

After engagement and refueling, refueling device 300 can be disengaged and used
15 for refueling another receiver aircraft 220, or, retracted to tanker aircraft 112.

For example, disengagement can be facilitated by engagement/disengagement control module 512 of controller 400.

In some examples, throughout the refueling process safety module 510 can monitor that refueling device 300 does not approach either aircraft 112, 220 in an unsafe
20 manner (or vice versa).

Although in the description above controller 400 was described as maintaining the roll angle of refueling device 300 as substantially the same as tanker aircraft 112, in some examples controller 400 can be configured to determine a roll angle of receiver aircraft 220 and maintain the roll angle of refueling device 300 as substantially the same
25 as receiver aircraft 220 when refueling device 300 is in an engaged state. For example, in Fig. 7 in place of, or, in addition to, obtaining a roll angle of tanker aircraft 112 (block 704) a roll angle of receiver aircraft 220 can be obtained (e.g. determined by a sensor on-board the receiver aircraft and obtained by external data interface module 514 of controller 400) and used to determine a desired roll angle of refueling device 300
30 (e.g., determined by roll angle control module 506 of controller 400).

- 27 -

It is to be understood that the invention is not limited in its application to the details set forth in the description contained herein or illustrated in the drawings. The invention is capable of other examples and of being practiced and carried out in various ways. Hence, it is to be understood that the phraseology and terminology employed
5 herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for designing other structures, methods, and systems for carrying out the several purposes of the presently disclosed subject matter.

10 It will also be understood that the system according to the invention may be, at least partly, implemented on a suitably programmed computer. Likewise, the invention contemplates a computer program being readable by a computer for executing the method of the invention. The invention further contemplates a non-transitory computer-readable memory tangibly embodying a program of instructions executable
15 by the computer for executing the method of the invention.

Those skilled in the art will readily appreciate that various modifications and changes can be applied to the examples of the invention as hereinbefore described without departing from its scope, defined in and by the appended claims.