# GEO-FIDUCIALS FOR UAV NAVIGATION

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application is based on U.S. Application No. 16/360,952, filed March 21, 2019, the contents of which are incorporated herein by reference in their entirety.

## TECHNICAL FIELD

**[0002]** This disclosure relates generally to unmanned aerial vehicles (UAVs), and in particular but not exclusively, relates to UAV navigation systems and methods for navigating UAVs.

## BACKGROUND INFORMATION

**[0003]** A UAV is a vehicle capable of air travel without a physically-present human operator. UAVs may be provisioned to perform various different missions, including payload delivery, exploration/reconnaissance, imaging, public safety, surveillance, or otherwise. The mission definition will often dictate a type of specialized equipment and/or configuration of the unmanned vehicle.

**[0004]** Safe and efficient UAV navigation relies upon the UAV having an accurate and precise navigation solution (for example, a latitude, longitude, and altitude). For example, a UAV may rely on a global positioning system (GPS) to generate a navigation solution in wide open environments; however, GPS navigation may lack the precision necessary to navigate a UAV in confined or crowded environments (such as an indoor UAV base having numerous UAVs). In addition, weather and other contingencies may degrade GPS signal strength, which may compromise the ability of a UAV to generate an accurate navigation solution by GPS. Some environments may experience degraded GPS performance, for example due to multipath, and others may be completely GPS-denied, i.e., may lack GPS signal altogether. These are merely exemplary scenarios, as other challenges characterize UAV navigation. Ultimately, the ability to generate a reliable, accurate, and precise navigation solution is important to efficient and safe UAV navigation.

## SUMMARY OF THE INVENTION

**[0004a]** According to a first aspect of the present invention, there is provided an unmanned aerial vehicle (UAV) navigation system, comprising:

a UAV charging pad or landing pad;

a plurality of fiducial markers positioned about the UAV charging pad or landing pad, each fiducial marker of the plurality being associated with a fiducial dataset storing a position of the fiducial marker, each fiducial dataset being stored in a fiducial map; and

a UAV having a navigation system coupled to the propulsion unit, the navigation system including a camera, a fiducial navigation sub-system, a non-fiducial navigation sub-system, and logic that when executed causes the UAV to perform operations including:

imaging a first fiducial marker of the plurality with the camera;

transitioning between a non-fiducial navigation mode, in which the UAV navigates without aid of the fiducial navigation sub-system, and a fiducial navigation mode in which the UAV navigates at least partially based upon the fiducial navigation sub-system;

accessing, from the fiducial map, the fiducial dataset storing the position of the first fiducial marker; and

navigating, based upon the fiducial dataset storing the position of the first fiducial marker, into alignment with and landing on the UAV charging pad or landing pad;

wherein the UAV includes further logic that when executed causes the UAV to perform additional operations comprising:

determining, while the UAV navigates within a fiducial navigation zone, a first navigation solution utilizing the fiducial navigation sub-system, and a second navigation solution utilizing the non-fiducial navigation sub-system;

validating the second navigation solution against the first navigation solution to determine if the non-fiducial navigation sub-system has a required position accuracy; and

navigating outside the fiducial navigation zone utilizing the non-fiducial navigation sub-system if the non-fiducial navigation sub-system has the required position accuracy.

**[0004b]** According to a second aspect of the present invention, there is provided an unmanned aerial vehicle (UAV) navigation method, comprising:

imaging a first fiducial marker of a plurality of fiducial markers using a fiducial navigation sub-system of a UAV, the UAV having a navigation system including the fiducial navigation sub-system and a non-fiducial navigation sub-system, the plurality of fiducial markers being positioned around a UAV charging pad or landing pad, each fiducial marker of the plurality being associated with a fiducial dataset storing a position of the fiducial marker;

transitioning the UAV from between non-fiducial navigation mode in which the UAV does not navigate based upon the fiducial navigation sub-system, and a fiducial navigation mode in which the UAV navigates at least partially based upon the fiducial navigation sub-system;

accessing, from a fiducial map stored onboard the UAV, the fiducial dataset storing the position of the first fiducial marker; and

navigating the UAV, based upon the fiducial dataset storing the position of the first fiducial marker, into alignment with and landing on the UAV charging pad or landing pad; and

the UAV navigation method further comprising:

determining, while the UAV navigates within a fiducial navigation zone, a first navigation solution utilizing the fiducial navigation sub-system, and a second navigation solution utilizing the non-fiducial navigation sub-system;

validating the second navigation solution against the first navigation solution to determine if the non-fiducial navigation sub-system has a required position accuracy; and

navigating outside the fiducial navigation zone utilizing the non-fiducial navigation sub-system if the non-fiducial navigation sub-system has the required position accuracy.

CLAIMS

What is claimed is:

1. An unmanned aerial vehicle, UAV, navigation system, comprising:

a UAV charging pad or landing pad;

a plurality of fiducial markers positioned about the UAV charging pad or landing pad, each fiducial marker of the plurality being associated with a fiducial dataset storing a position of the fiducial marker, each fiducial dataset being stored in a fiducial map; and

a UAV having a navigation system including a camera, a fiducial navigation sub-system, a non-fiducial navigation sub-system, and logic that when executed causes the UAV to perform operations including:

imaging a first fiducial marker of the plurality with the camera;

transitioning between a non-fiducial navigation mode, in which the UAV navigates without aid of the fiducial navigation sub-system, and a fiducial navigation mode in which the UAV navigates at least partially based upon the fiducial navigation sub-system;

accessing, from the fiducial map, the fiducial dataset storing the position of the first fiducial marker; and

navigating, based upon the fiducial dataset storing the position of the first fiducial marker, into alignment with and landing on the UAV charging pad or landing pad;

wherein the UAV includes further logic that when executed causes the UAV to perform additional operations comprising:

determining, while the UAV navigates within a fiducial navigation zone, a first navigation solution utilizing the fiducial navigation sub-system, and a second navigation solution utilizing the non-fiducial navigation sub-system;

validating the second navigation solution against the first navigation solution to determine if the non-fiducial navigation sub-system has a required position accuracy; and

navigating outside the fiducial navigation zone utilizing the non-fiducial navigation sub-system if the non-fiducial navigation sub-system has the required position accuracy.

2. The UAV navigation system of Claim 1, wherein the plurality of fiducial markers includes the first fiducial marker positioned adjacent to a first side of the UAV charging pad or landing pad, and a second fiducial marker positioned adjacent to a second side of the UAV charging pad or landing pad, to enable imaging of at least one of the first or second fiducial markers by the camera immediately prior to landing.

3. The UAV navigation system of Claim 2, further comprising a third fiducial marker positioned adjacent to the first fiducial marker and radially outward from the UAV charging pad or landing pad, and a fourth fiducial marker positioned adjacent to the second fiducial marker and radially outward from the UAV charging pad or landing pad,

wherein the first and second fiducial markers are smaller than the third and fourth fiducial markers to enable imaging of at least one of the first or second fiducial markers from an altitude at which the third and fourth fiducial markers are outside a field of view of the camera.

4. The UAV navigation system of Claim 2, further comprising a fifth fiducial marker positioned adjacent to a third side of the UAV charging pad or landing pad and a sixth fiducial marker positioned adjacent to a fourth side of the UAV charging pad or landing pad, to enable imaging of at least one of the first, second, fifth or sixth fiducial markers by the camera immediately prior to landing.

5. The UAV navigation system of Claim 3, wherein the UAV charging pad or landing pad is a first UAV charging pad or landing pad, the UAV navigation system further comprising a second UAV charging pad or landing pad separated from the first UAV charging pad or landing pad by a seventh fiducial marker, which is larger than the first and third fiducial markers, to enable the UAV to determine a navigation solution based on the seventh fiducial marker at a higher altitude than the UAV can determine the navigation solution based on the first and third fiducial markers.

6. The UAV navigation system of claim 1, wherein the charging pad or landing pad is a first UAV charging pad or landing pad, the UAV navigation system further comprising a second UAV charging pad or landing pad separated from the first UAV

charging pad or landing pad by a third fiducial marker of the plurality of fiducial markers that is larger than the first fiducial marker and a second fiducial marker of the plurality of fiducial markers, to enable the UAV to determine a navigation solution based on the third fiducial marker before the camera can image the first and second fiducial markers, wherein the first fiducial marker is positioned adjacent to a first side of the first UAV charging pad or landing pad, the second fiducial marker positioned adjacent to the first fiducial marker and radially outward from the first UAV charging pad or landing pad, and wherein the first fiducial marker is smaller than the second fiducial marker to enable imaging of the first fiducial marker from an altitude at which the second fiducial marker is outside a field of view of the camera.

7. The UAV navigation system of Claim 2, further comprising a third fiducial marker and a fourth fiducial marker positioned adjacent to an access point through a perimeter of a storage facility, wherein the UAV includes further logic that, when executed causes the UAV to perform additional operations comprising:

imaging at least one of the third fiducial marker or the fourth fiducial marker;

accessing, from the fiducial map, the fiducial dataset storing the position of the at least one imaged third or fourth fiducial marker; and

navigating through the access point based upon the fiducial dataset storing the position of the at least one imaged third or fourth fiducial marker.

8. The UAV navigation system of Claim 2 or Claim 6, wherein the first fiducial marker is adjacently surrounded by a contrasting region having an overall border gray value that is no darker than a fiducial gray value of the first fiducial marker.

9. The UAV navigation system of Claim 1, wherein:

the UAV is a first UAV, the UAV navigation system further comprising a second UAV having a UAV fiducial marker associated with a dynamic fiducial dataset storing a real-time position of the UAV fiducial marker in the fiducial map, wherein the first UAV includes further logic that when executed causes the first UAV to perform further operations including:

imaging the UAV fiducial marker of the second UAV with the camera;

accessing, from the fiducial map, the dynamic fiducial dataset storing the real-time position of the UAV fiducial marker; and

navigating around the second UAV based upon the real-time position of the UAV fiducial marker.

10. The UAV navigation system of Claim 1, the UAV including further logic that when executed causes the UAV to perform additional operations comprising:

storing a UAV position of the UAV acquired immediately prior to landing on the UAV charging pad or landing pad or while landed on the UAV charging pad or landing pad;

monitoring the UAV position while landed to detect a threshold motion level after the UAV lands; and

invalidating the UAV position if the threshold motion level is detected.

11. The UAV navigation system of Claim 1, the UAV including further logic that when executed causes the UAV to perform additional operations comprising:

executing a test flight plan that includes taking off from the UAV charging pad or landing pad, determining a navigation solution based upon the fiducial navigation sub-system while the UAV hovers over the UAV charging pad or landing pad, and landing on the UAV charging pad or landing pad.

12. The UAV navigation system of Claim 3, wherein the first, second, third, and fourth fiducial markers are each associated with a common heading, to assist the UAV to navigate into alignment with and land on the UAV charging pad or landing pad.

13. The UAV navigation system of Claim 1,

wherein the fiducial map is a first fiducial map corresponding to a first geographic area,

the UAV including further logic that, when executed causes the UAV to replace the first fiducial map with a second fiducial map corresponding to a second geographic area, when the UAV operates in the second geographic area,

wherein the first fiducial map and the second fiducial map each store an identical fiducial marker code.

14. The UAV navigation system of Claim 1,

wherein the plurality of fiducial markers includes the first fiducial marker, a second fiducial marker, a third fiducial marker, and a fourth fiducial marker, all positioned adjacent to and on different sides of the UAV charging pad or landing pad,

wherein imaging the fiducial marker includes imaging the first fiducial marker, the second fiducial marker, the third fiducial marker, and the fourth fiducial marker, and

wherein navigating includes determining a navigation solution of the UAV based upon a position of the first fiducial marker, a position of the second fiducial marker, a position of the third fiducial marker, and a position of the fourth fiducial marker.

15. The UAV navigation system of Claim 1, wherein each fiducial marker is associated with a respective fiducial dataset and wherein the method comprises determining a navigation solution for the UAV based on the position of the imaged fiducial marker identified from the fiducial dataset associated with the respective marker, and navigating based on the determined navigation solution.

16. An unmanned aerial vehicle, UAV, navigation method, comprising:

imaging a first fiducial marker of a plurality of fiducial markers using a fiducial navigation sub-system of a UAV, the UAV having a navigation system including the fiducial navigation sub-system and a non-fiducial navigation sub-system, the plurality of fiducial markers being positioned around a UAV charging pad or landing pad, each fiducial marker of the plurality being associated with a fiducial dataset storing a position of the fiducial marker;

transitioning the UAV between a non-fiducial navigation mode in which the UAV does not navigate based upon the fiducial navigation sub-system, and a fiducial navigation mode in which the UAV navigates at least partially based upon the fiducial navigation sub-system;

accessing, from a fiducial map stored onboard the UAV, the fiducial dataset storing the position of the first fiducial marker; and

navigating the UAV, based upon the fiducial dataset storing the position of the first fiducial marker, into alignment with and landing on the UAV charging pad or landing pad; and

the UAV navigation method further comprising:

determining, while the UAV navigates within a fiducial navigation zone, a first navigation solution utilizing the fiducial navigation sub-system, and a second navigation solution utilizing the non-fiducial navigation sub-system;

validating the second navigation solution against the first navigation solution to determine if the non-fiducial navigation sub-system has a required position accuracy; and

navigating outside the fiducial navigation zone utilizing the non-fiducial navigation sub-system if the non-fiducial navigation sub-system has the required position accuracy.

17. The UAV navigation method of Claim 16, wherein the plurality of fiducial markers includes a first group of fiducial markers positioned around the UAV charging pad or landing pad and a second group of fiducial markers positioned around an access point into a storage facility, wherein navigating the UAV includes navigating through the access point based upon the second group of fiducial markers.

18. The UAV navigation method of Claim 17, wherein the plurality of fiducial markers includes a third group of fiducial markers positioned outside the storage facility and proximal to the access point, wherein navigating includes navigating to the access point based upon the third group of fiducial markers.

19. The UAV navigation method of Claim 16, further comprising:

wherein the fiducial map is a first fiducial map associated with a first geographical area,

determining, based on a geographical position of the UAV retrieved using the non-fiducial navigation sub-system, whether the UAV is located in a second geographical area, and

replacing the first fiducial map with a second fiducial map if the UAV is located in the second geographical area.

20. The UAV navigation method of Claim 19, wherein the first and second fiducial maps each store an identical fiducial marker code.