Therefore it would be desirable to have a system and method that takes into account at least some of the issues discussed above, as well as other possible issues.

BRIEF SUMMARY

Example implementations of the present disclosure are directed to an improved technique for landing an unmanned aerial vehicle (UAV) in a contingency scenario. Example implementations provide a contingency management system and procedure for a UAV that may improve operational safety with respect to the risk exhibited to third parties in the air and on the ground by enabling automated landings in contingency situations.

The procedure in some example implementations may follow a systematic approach based on a tiered quantitative risk assessment conducted by analyzing data covering factors affecting risk. This may enable use of data-driven risk assessments in handling contingencies. Safe landing zones (SLZs) may be introduced as alternate landing sites as a means to avoid flight termination or landings in unsafe areas in situations where a planned mission cannot continue.

The present disclosure thus includes, without limitation, the following example implementations.

Some example implementations provide a method of performing a contingency landing procedure for an unmanned aerial vehicle (UAV), the method comprising: determining candidate safe landing zones (SLZs) within an estimated current range of the UAV from a current position; generating trajectories for landing the UAV in respective ones of the candidate SLZs based on environmental and operational factors that affect flight of the UAV from the current position to the respective ones of the candidate SLZs, wherein generating the trajectories includes for a candidate SLZ, interpolating a straight line from the current position to the candidate SLZ and thereby generating a trajectory to the candidate SLZ, wherein the straight line is a certain distance and includes a total number of discrete points over the certain distance; calculating risk values that quantify third-party risk associated with operation of the UAV along respective ones of the trajectories to the respective ones of the candidate SLZs, a lowest of the risk values associated with a trajectory from the current position to a selected one of the candidate

SLZs; generating or receiving a risk map of a geographic area of operation of the UAV, the risk map including risk zones with respective risk categories having respective risk weighting factors that quantify third-party risk associated with operation of the UAV in the risk zones, wherein the trajectories intersect various ones of the risk zones, and the risk values are calculated based on the respective risk weighting factors; wherein calculating the risk values includes for the trajectory: a) separating the trajectory into segments at points of intersection with one or more of the risk zones; and b) calculating a risk value for the candidate SLZ from the segments and risk weighting factors for the one or more of the risk zones; wherein separating the trajectory includes for each risk zone of the one or more risk zones: a) determining a ratio of a number of discrete points on the trajectory located inside the risk zone to the total number of the discrete points of the trajectory; and b) calculating the product of the ratio and the certain distance and thereby an intersection length of the risk zone; calculating a flight termination risk value that quantifies third-party risk associated with immediately landing the UAV at the current position; performing a comparison of the lowest of the risk values with the flight termination risk value; and executing a sequence to operate the UAV along the trajectory

Claims:

1. An apparatus (120, 500) for causing an unmanned aerial vehicle (UAV) (110) to perform a contingency landing procedure, the apparatus comprising:

a memory (504) configured to store computer-readable program code (506); and

processing circuitry (502) configured to access the memory and execute the computer-readable program code to cause the apparatus to at least:

determine (302) candidate safe landing zones (SLZs) (190) within an estimated current range of the UAV from a current position (112);

generate (304) trajectories (170) for landing the UAV in respective ones of the candidate SLZs based on environmental and operational factors that affect flight of the UAV from the current position to the respective ones of the candidate SLZs;

calculate (308) risk values that quantify third-party risk associated with operation of the UAV along respective ones of the trajectories to the respective ones of the candidate SLZs, a lowest of the risk values associated with a trajectory from the current position to a selected one of the candidate SLZs;

calculate (310) a flight termination risk value that quantifies third-party risk associated with immediately landing the UAV at the current position;

perform (312) a comparison of the lowest of the risk values with the flight termination risk value; and

execute (314) a sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, or immediately land the UAV at the current position, based on the comparison.

2. The apparatus (120, 500) of claim 1, wherein at least one of:

the processing circuitry (502) is further configured to cause the apparatus located onboard the UAV (110) to autonomously execute the sequence without input from a ground control station (GCS) (130), wherein the GCS and the UAV are part of an unmanned aerial system (101); and

the UAV (110) is part of an unmanned aerial system (101) that also includes a ground control station (GCS) (130), the apparatus is located at the GCS, and the apparatus is caused to execute the sequence through remote control of the UAV from the GCS.

3. The apparatus (120, 500) of any of claims 1-2, wherein the processing circuitry (502) is configured to execute the computer-readable program code (506) to further cause the apparatus to:

generate or receive (306) a risk map (200) of a geographic area of operation of the UAV (110), the risk map including risk zones (220) with respective risk categories having respective risk weighting factors that quantify third-party risk associated with operation of the UAV in the risk zones,

wherein the trajectories (170) intersect various ones of the risk zones, and the risk values are calculated (308) based on the respective risk weighting factors.

4. The apparatus (120, 500) of claim 3, wherein the apparatus caused to generate (304) the trajectories (170) includes, for a candidate SLZ (190), the apparatus caused to interpolate a straight line from the current position (112) to the candidate SLZ and thereby generate a trajectory to the candidate SLZ, and

wherein the apparatus caused to calculate (308) the risk values includes, for the trajectory, the apparatus caused to:

separate (308A) the trajectory into segments (170A, 170B) at points of intersection with one or more of the risk zones (220); and

calculate (308B) a risk value for the candidate SLZ from the segments and risk weighting factors for the one or more of the risk zones.

5. The apparatus (120, 500) of claim 4, wherein the straight line is a certain distance and includes a total number of discrete points over the certain distance, and the apparatus caused to separate (308A) the trajectory (170) includes, for each risk zone (220) of the one or more risk zones, the apparatus caused to:

determine (308A1) a ratio of a number of discrete points on the trajectory located inside the risk zone to the total number of the discrete points of the trajectory; and

calculate (308A2) the product of the ratio and the certain distance and thereby an intersection length of the risk zone.

6. The apparatus (120, 500) of claim 5, wherein the apparatus caused to calculate (308B) the risk value for the candidate SLZ (190) includes the apparatus caused to:

~~calculate (308B1) risk-zone risk values for respective ones of the one or more risk zones (220), a risk-zone risk value for the risk zone being the product of the intersection length of the risk zone and a risk weighting factor of a risk category of the risk zone; and~~

~~sum (308B2) the risk-zone risk values to calculate the risk value for the candidate SLZ.~~

~~7. The apparatus (120, 500) of claim 3, wherein the apparatus is caused to execute (314) the sequence to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190), and utilizing an updated current position (112) along the trajectory, the processing circuitry (502) is configured to execute the computer-readable program code (506) to cause the apparatus to further:~~

~~generate or receive (316) an updated risk map (200) of the geographic area of operation of the UAV (110), the updated risk map including the risk zones (220) with respective updated risk categories having respective updated risk weighting factors;~~

~~calculate (318) an updated lowest of the risk values and an updated flight termination risk value based on the respective updated risk weighting factors; and~~

~~interrupt (320) the sequence to immediately land the UAV at the updated current position when the updated lowest of the risk values is greater than the updated flight termination risk value.~~

~~8. The apparatus (120, 500) of any of claims 1-7, wherein at least one of:~~

~~the apparatus is caused to execute (314) the sequence to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190) when the lowest of the risk values is less than or equal to the flight termination risk value, and to immediately land the UAV at the current position (112) when the lowest of the risk values is greater than the flight termination risk value;~~

~~the apparatus is caused to execute (314) the sequence to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190), and utilizing an updated current position (112) along the trajectory, the processing circuitry (502) is configured to execute the computer-readable program code (506) to cause the apparatus to further: calculate (318) an updated lowest of the risk values and an updated flight termination risk value; and interrupt (320) the sequence to immediately land the UAV at~~

the updated current position when the updated lowest of the risk values is greater than the updated flight termination risk value; and

the apparatus is caused to execute (314) the sequence to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190), and utilizing an updated current position (112) along the trajectory, the processing circuitry (502) is configured to execute the computer-readable program code (506) to cause the apparatus to further: determine (322) updated candidate SLZs within an updated estimated current range of the UAV from the updated current position, the updated candidate SLZs including the selected one of the candidate SLZs; generate (324) updated trajectories for landing the UAV in respective ones of the updated candidate SLZs; calculate (326) updated risk values and an updated flight termination risk value, a lowest of the updated risk values associated with an updated trajectory from the updated current position to a selected one of the updated candidate SLZs; perform (328) a comparison of the lowest of the updated risk values with the updated flight termination risk value; and execute (330) an updated sequence to operate the UAV along the updated trajectory to the selected one of the updated candidate SLZs, or immediately land the UAV at the updated current position, based on the comparison.

9. A method (300) of performing a contingency landing procedure for an unmanned aerial vehicle (UAV) (110), the method comprising:

determining (302) candidate safe landing zones (SLZs) (190) within an estimated current range of the UAV from a current position (112);

generating (304) trajectories (170) for landing the UAV in respective ones of the candidate SLZs based on environmental and operational factors that affect flight of the UAV from the current position to the respective ones of the candidate SLZs;

calculating (308) risk values that quantify third-party risk associated with operation of the UAV along respective ones of the trajectories to the respective ones of the candidate SLZs, a lowest of the risk values associated with a trajectory from the current position to a selected one of the candidate SLZs;

calculating (310) a flight termination risk value that quantifies third-party risk associated with immediately landing the UAV at the current position;

performing (312) a comparison of the lowest of the risk values with the flight termination risk value; and

executing (314) a sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, or immediately land the UAV at the current position, based on the comparison.

10. The method (300) of claim 9, wherein at least one of:

the UAV (110) is part of an unmanned aerial system (101) that also includes a ground control station (GCS) (130), the method is performed onboard the UAV, and the sequence is autonomously executed without input from the GCS; and

the UAV (110) is part of an unmanned aerial system (101) that also includes a ground control station (GCS) (130), the method is performed at the GCS, and the sequence is executed through remote control of the UAV from the GCS.

11. The method (300) of any of claims 9-10 further comprising:

generating or receiving (306) a risk map (200) of a geographic area of operation of the UAV (110), the risk map including risk zones (220) with respective risk categories having respective risk weighting factors that quantify third-party risk associated with operation of the UAV in the risk zones,

wherein the trajectories (170) intersect various ones of the risk zones, and the risk values are calculated (308) based on the respective risk weighting factors.

12. The method (300) of claim 11, wherein generating (304) the trajectories (170) includes for a candidate SLZ (190), interpolating a straight line from the current position (112) to the candidate SLZ and thereby generating a trajectory to the candidate SLZ, and

wherein calculating (308) the risk values includes for the trajectory:

separating (308A) the trajectory into segments (170A, 170B) at points of intersection with one or more of the risk zones (220); and

calculating (308B) a risk value for the candidate SLZ from the segments and risk weighting factors for the one or more of the risk zones.

13. The method (300) of claim 12, wherein the straight line is a certain distance and includes a total number of discrete points over the certain distance, and separating (308A) the trajectory (170) includes for each risk zone (220) of the one or more risk zones:

~~determining (308A1) a ratio of a number of discrete points on the trajectory located inside the risk zone to the total number of the discrete points of the trajectory; and~~

~~calculating (308A2) the product of the ratio and the certain distance and thereby an intersection length of the risk zone.~~

~~14. The method (300) of claim 13, wherein calculating (308B) the risk value for the candidate SLZ (190) includes:~~

~~calculating (308B1) risk-zone risk values for respective ones of the one or more risk zones (220), a risk-zone risk value for the risk zone being the product of the intersection length of the risk zone and a risk weighting factor of a risk category of the risk zone; and~~

~~summing (308B2) the risk-zone risk values to calculate the risk value for the candidate SLZ.~~

~~15. The method (300) of any of claims 9-14, wherein at least one of:~~

~~the sequence is executed (314) to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190) when the lowest of the risk values is less than or equal to the flight termination risk value, and to immediately land the UAV at the current position (112) when the lowest of the risk values is greater than the flight termination risk value;~~

~~the sequence is executed (314) to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190), and utilizing an updated current position (112) along the trajectory, the method further comprises: calculating (318) an updated lowest of the risk values and an updated flight termination risk value; and interrupting (320) the sequence to immediately land the UAV at the updated current position when the updated lowest of the risk values is greater than the updated flight termination risk value; and~~

~~the sequence is executed (314) to operate the UAV (110) along the trajectory (170) to the selected one of the candidate SLZs (190), and utilizing an updated current position (112) along the trajectory, the method further comprises: determining (322) updated candidate SLZs within an updated estimated current range of the UAV from the updated current position, the updated candidate SLZs including the selected one of the candidate SLZs; generating (324) updated trajectories for landing the UAV in respective~~

~~ones of the updated candidate SLZs; calculating (326) updated risk values and an updated flight termination risk value, a lowest of the updated risk values associated with an updated trajectory from the updated current position to a selected one of the updated candidate SLZs; performing (328) a comparison of the lowest of the updated risk values with the updated flight termination risk value; and executing (330) an updated sequence to operate the UAV along the updated trajectory to the selected one of the updated candidate SLZs, or immediately land the UAV at the updated current position, based on the comparison.~~

1. An apparatus for causing an unmanned aerial vehicle (or UAV) to perform a contingency landing procedure, the apparatus comprising:

a memory configured to store computer-readable program code; and

processing circuitry configured to access the memory and execute the computer-readable program code to cause the apparatus to at least:

determine candidate safe landing zones (or SLZs) within an estimated current range of the UAV from a current position;

generate trajectories for landing the UAV in respective ones of the candidate SLZs based on environmental and operational factors that affect flight of the UAV from the current position to the respective ones of the candidate SLZs;

for a candidate SLZ, interpolate a straight line from the current position to the candidate SLZ and thereby generate a trajectory to the candidate SLZ, wherein the straight line is a certain distance and includes a total number of discrete points over the certain distance;

calculate risk values that quantify third-party risk associated with operation of the UAV along respective ones of the trajectories to the respective ones of the candidate SLZs, a lowest of the risk values being associated with a trajectory from the current position to a selected one of the candidate SLZs;

generate or receive a risk map of a geographic area of operation of the UAV, the risk map including risk zones with respective risk categories having respective risk weighting factors that quantify third-party risk associated with operation of the UAV in the risk zones, wherein the trajectories intersect various ones of the risk zones, and the risk values are calculated based on the respective risk weighting factors;

for a trajectory to the candidate SLZ, separate the trajectory into segments at points of intersection with one or more of the risk zones and calculate a risk value for the candidate SLZ from the segments and risk weighting factors for the one or more of the risk zones;

for each risk zone of the one or more risk zones, determine a ratio of a number of discrete points on the trajectory located inside the risk zone to the total number of the discrete points of the trajectory and calculate the product of the ratio and the certain distance and thereby an intersection length of the risk zone;

calculate a flight termination risk value that quantifies third-party risk associated with immediately landing the UAV at the current position;

perform a comparison of the lowest of the risk values with the flight termination risk value;

execute a sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, or immediately land the UAV at the current position, based on the comparison.

2. The apparatus of claim 1, wherein the apparatus is located onboard the UAV and the processing circuitry is further configured to cause the apparatus located onboard the UAV to autonomously execute the sequence without input from a ground control station (or GCS), wherein the GCS and the UAV are part of an unmanned aerial system.

3. The apparatus of any of claims 1-2, wherein the UAV is part of an unmanned aerial system that also includes a ground control station (GCS), the apparatus is located at the GCS, and the apparatus is caused to execute the sequence through remote control of the UAV from the GCS.

4. The apparatus of any of claims 1-3, wherein the apparatus caused to calculate the risk value for the candidate SLZ includes to be caused to:

calculate risk-zone risk values for respective ones of the one or more risk zones, a risk-zone risk value for the risk zone being the product of the intersection length of the risk zone and a risk weighting factor of a risk category of the risk zone; and

sum the risk-zone risk values to calculate the risk value for the candidate SLZ.

5. The apparatus of any of claims 1-3, wherein the apparatus is caused to execute the sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, and utilizing an updated current position along the trajectory, the processing circuitry is configured to execute the computer-readable program code to cause the apparatus to further:

generate or receive an updated risk map of the geographic area of operation of the UAV, the updated risk map including the risk zones with respective updated risk categories having respective updated risk weighting factors;

calculate an updated lowest of the risk values and an updated flight termination risk value based on the respective updated risk weighting factors; and

interrupt the sequence to immediately land the UAV at the updated current position when the updated lowest of the risk values is greater than the updated flight termination risk value.

6. The apparatus of any of claims 1-5, wherein the apparatus is caused to execute the sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs when the lowest of the risk values is less than or equal to the flight termination risk value, and to immediately land the UAV at the current position when the lowest of the risk values is greater than the flight termination risk value.

7. The apparatus of any of claims 1-6, wherein the apparatus is caused to execute the sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, and utilizing an updated current position along the trajectory, the processing circuitry is configured to execute the computer-readable program code to cause the apparatus to further:

calculate an updated lowest of the risk values and an updated flight termination risk value; and

interrupt the sequence to immediately land the UAV at the updated current position when the updated lowest of the risk values is greater than the updated flight termination risk value.

8. The apparatus of any of claims 1-7, wherein the apparatus is caused to execute the sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, and utilizing an updated current position along the trajectory, the

processing circuitry is configured to execute the computer-readable program code to cause the apparatus to further:

determine updated candidate SLZs within an updated estimated current range of the UAV from the updated current position, the updated candidate SLZs including the selected one of the candidate SLZs;

generate updated trajectories for landing the UAV in respective ones of the updated candidate SLZs;

calculate updated risk values and an updated flight termination risk value, a lowest of the updated risk values associated with an updated trajectory from the updated current position to a selected one of the updated candidate SLZs;

perform a comparison of the lowest of the updated risk values with the updated flight termination risk value; and

execute an updated sequence to operate the UAV along the updated trajectory to the selected one of the updated candidate SLZs, or immediately land the UAV at the updated current position, based on the comparison.

9. A method of performing a contingency landing procedure for an unmanned aerial vehicle (UAV), the method comprising:

determining candidate safe landing zones (SLZs) within an estimated current range of the UAV from a current position;

generating trajectories for landing the UAV in respective ones of the candidate SLZs based on environmental and operational factors that affect flight of the UAV from the current position to the respective ones of the candidate SLZs, wherein generating the trajectories includes for a candidate SLZ, interpolating a straight line from the current position to the candidate SLZ and thereby generating a trajectory to the candidate SLZ, wherein the straight line is a certain distance and includes a total number of discrete points over the certain distance;

calculating risk values that quantify third-party risk associated with operation of the UAV along respective ones of the trajectories to the respective ones of the candidate SLZs, a lowest of the risk values associated with a trajectory from the current position to a selected one of the candidate SLZs;

generating or receiving a risk map of a geographic area of operation of the UAV, the risk map including risk zones with respective risk categories having respective risk weighting factors that quantify third-party risk associated with operation of the UAV in

the risk zones, wherein the trajectories intersect various ones of the risk zones, and the risk values are calculated based on the respective risk weighting factors;

wherein calculating the risk values includes for the trajectory: a) separating the trajectory into segments at points of intersection with one or more of the risk zones; and b) calculating a risk value for the candidate SLZ from the segments and risk weighting factors for the one or more of the risk zones;

wherein separating the trajectory includes for each risk zone of the one or more risk zones: a) determining a ratio of a number of discrete points on the trajectory located inside the risk zone to the total number of the discrete points of the trajectory; and b) calculating the product of the ratio and the certain distance and thereby an intersection length of the risk zone;

calculating a flight termination risk value that quantifies third-party risk associated with immediately landing the UAV at the current position;

performing a comparison of the lowest of the risk values with the flight termination risk value; and

executing a sequence to operate the UAV along the trajectory to the selected one of the candidate SLZs, or immediately land the UAV at the current position, based on the comparison.

10. The method of claim 9, wherein the UAV is part of an unmanned aerial system that also includes a ground control station (GCS), the method is performed onboard the UAV, and the sequence is autonomously executed without input from the GCS.

11. The method of any of claims 9-10, wherein the UAV is part of an unmanned aerial system that also includes a ground control station (GCS), the method is performed at the GCS, and the sequence is executed through remote control of the UAV from the GCS.

12. The method of any of claims 9-11, wherein calculating the risk value for the candidate SLZ includes:

calculating risk-zone risk values for respective ones of the one or more risk zones, a risk-zone risk value for the risk zone being the product of the intersection length of the risk zone and a risk weighting factor of a risk category of the risk zone; and

summing the risk-zone risk values to calculate the risk value for the candidate SLZ.

13. The method of any of claims 9-12, wherein the sequence is executed to operate the UAV along the trajectory to the selected one of the candidate SLZs when the lowest of the risk values is less than or equal to the flight termination risk value, and to immediately land the UAV at the current position when the lowest of the risk values is greater than the flight termination risk value.

14. The method of any of claims 9-13, wherein the sequence is executed to operate the UAV along the trajectory to the selected one of the candidate SLZs, and utilizing an updated current position along the trajectory, the method further comprises:

calculating an updated lowest of the risk values and an updated flight termination risk value; and

interrupting the sequence to immediately land the UAV at the updated current position when the updated lowest of the risk values is greater than the updated flight termination risk value.

15. The method of any of claims 9-14, wherein the sequence is executed to operate the UAV along the trajectory to the selected one of the candidate SLZs, and utilizing an updated current position along the trajectory, the method further comprises:

determining updated candidate SLZs within an updated estimated current range of the UAV from the updated current position, the updated candidate SLZs including the selected one of the candidate SLZs;

generating updated trajectories for landing the UAV in respective ones of the updated candidate SLZs;

calculating updated risk values and an updated flight termination risk value, a lowest of the updated risk values associated with an updated trajectory from the updated current position to a selected one of the updated candidate SLZs;

performing a comparison of the lowest of the updated risk values with the updated flight termination risk value; and

executing an updated sequence to operate the UAV along the updated trajectory to the selected one of the updated candidate SLZs, or immediately land the UAV at the updated current position, based on the comparison.