WEIGHT-ON-WHEEL DETECTION AND GROUND-FLIGHT-MODE SWITCHING FOR UAVS

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Abstract—This paper describes the development of a weight-on-wheel detection system for an Unmanned Aerial Vehicle (UAV) and the development of a criterion for ground-flight-mode switching. Redundant methods for weight-on-wheel detection were developed using both a direct measurement of the contact and estimations based on other available information. The redundant data makes it possible to identify possible measurement errors through inconsistencies in the results of the different methods. Taking that possibility into account, the ground-flight-mode switching algorithm was structured in layers where successively less rigorous criteria are used to determine the control mode and the adopted result is the result of the most rigorous layer that could provide an answer. Such procedure yields information on both, the mode of the aircraft and the rigor used to determine that mode, making it possible to act more carefully when the result is less certain.

Keywords—Sensors and actuators in robotics, Aerial/Autonomous robotics, Data fusion

Resumo—Este artigo descreve o desenvolvimento de um sistema para deteção de peso nas rodas de um veículo aéreo não tripulado (VANT) e o desenvolvimento de um critério para chaveamento entre os modos de voo e de solo. Métodos redundantes para a deteção de peso nas rodas utilizando tanto uma medição direta do contato quanto estimativas baseadas em outras informações disponíveis. Os dados redundantes possibilitam a identificação de possíveis erros de medição através de inconsistências nos resultados de diferentes métodos. Levando essa possibilidade em consideração, o chaveamento entre os modos de solo e de voo é estruturado em camadas onde critérios sucessivamente menos rigorosos são usados para determinar o modo de controle e o resultado adotado é o resultado da camada mais rigorosa que pode encontrar um resultado. Tal procedimento resulta em informações sobre tanto o modo da aeronave quanto sobre o rigor utilizado para determinar este modo, sendo possível agir com mais cuidado quando o resultado é menos certo.

Palavras-chave—Sensores e atuadores em robótica, Robótica aérea/autônoma, Fusão de dados.

1 Nomenclature

1.1 Symbols

• $\theta$: pitch angle
• $\phi$: roll angle
• $h$: altitude
• $v$: speed
• $air$: aircraft flying
• $gnd$: aircraft on ground
• $data$: set of data from all the sensors available

1.2 Indices

• $gnd$: relative to the ground
• $0...t$: from instant 0 to t

2 Introduction

Work reported herein was developed within the ULTRA (Unmanned Low-cost Testing Research Aircraft) project. This project is a project of the Institute of Aircraft Systems Engineering, at the Hamburg University of Technology, and encompasses research and education establishing flight test capabilities based on industry standard software and hardware components (Krings et al., 2013). Among the aims of the ULTRA project is the development of an autonomous take-off and landing capability. This paper reports on the development of a system for detecting the contact of the wheels of the aircraft with the ground, which is necessary for the development of autonomous take-off and landing processes.

The detection of the contact of the wheels with the ground was performed combining the data from both the previously available sensors on the aircraft and a specific contact detection sensor. This sensor is shown in figure 1. It consists of a lever positioned near the wheel of the aircraft which is pressed when the wheel touches the ground. The movement of the lever, then, deforms a spring, producing a force on a force sensor.

Additionally to this concept, other auxiliary predictors were implemented using the data already available from the sensors in the aircraft. First of all, the restriction of the degrees of freedom of the aircraft when it is on ground was used to determine if it is possible that the airplane is on ground and to determine if it is almost certain that the airplane is on ground. In the last case, a smaller margin was allowed for the constrained variables. Those limits were also useful for helping in the prediction of whether or not the lever from one of the weight-on-wheel sensor is broken.

Moreover, probabilistic models were developed based on the Bayes theorem (Papoulis and Pillai, 2002). Those models aimed to predict the probability of take-off, landing and being on
The final assembly is shown in figure 1.

Figure 1: Final assembly of the weight-on-wheel sensor.

The probabilities calculated through the Bayes theorem were then taken into account within a simplified Bayes model of the aircraft and its sensors. According to this model, it was possible to both filter and fuse the obtained data applying the Bayes theorem to a model of the sensors.

Finally, all information obtained with the methods outlined above was fused in order to provide a reliable prediction of whether or not the aircraft is on ground. First, the data from the weight-on-wheel sensors were provided in conjunction with the prediction of whether or not the levers are broken. The data from the weight-on-wheel sensor might not be enough when the lever of one of the weight-on-wheel sensors is broken. Therefore, a method was developed to consider all the available predictions. The method developed was inspired on (Brooks, 1986). In this method first of all, the prediction is divided in both wheels and their time derivatives. Together with the degrees of freedom of the aircraft provided a mean of predicting whether or not the aircraft is almost certainly on ground. Afterwards, for each of those two predictions, several layers were developed in order to attempt to make a prediction. The layers are organized according to a hierarchy where each layer’s goal is to predict whether both or any of the wheels are on ground. If the criterion for that prediction to be successful are not obeyed, the next layer is consulted.

3 Weight-on-Wheel Sensor

The direct detection of the weight-on-wheel was performed with a lever positioned beside each wheel. The lever is connected to a spring which produces a force on a Force Sensing Resistor$^{\text{TM}}$ (FSR, Interlink Electronics, Santa Barbara, CA). The final assembly is shown in figure 1.

The resistance in the Force Sensing Resistor$^{\text{TM}}$ (FSR, Interlink Electronics, Santa Barbara, CA) is approximately proportional to the inverse of the force applied to it. Nevertheless, it is preferable to have an output proportional to the force. This enhances the understanding of the output of the sensor and presents better flexibility in relation to the range of the force, which allows the circuit to be designed without a previous knowledge of the range of the force. For that purpose, a circuit was designed to produce the following output:

$$v_{out} = \left(\frac{20}{21} - \frac{11}{21} \frac{13K}{R_1}\right) v_{ref}$$

(1)

Additionally, a second order anti-aliasing filter with a cut frequency of $30\,Hz$ was added to the circuit. This filter is intended to avoid the occurrence of aliasing when the frequency range of each applied force signal exceeds half of the sampling frequency of $62\,Hz$ according to the Nyquist-Shannon sampling theorem (Jerri, 1977).

4 Degrees of Freedom Analysis

The contact of the aircraft with the ground constrains altitude $h$, the pitch angle $\theta$, the roll angle $\phi$ and their time derivatives. Together with the degrees of freedom, the speed of the aircraft was considered since a high speed indicates that the aircraft is not likely to remain on ground.

The reduction on the degrees of freedom can not be unequivocally determined due to the roughness of the ground and other sources of uncertainties. Considering this fact, two different criteria were developed to determine if the aircraft is on ground, one that makes the best effort to avoid false negatives, indicating whether or not the aircraft is possibly on ground, and another that makes the best effort to avoid false positives, indicating whether or not the aircraft is almost certainly on ground.

The criterion for determining whether the aircraft is possibly on ground consists in verifying if the coordinates of the aircraft obey all the following constrains: $|\theta - 8.6^\circ| \leq 20^\circ$, $|\phi| \leq 10^\circ$ and $h \leq 5m$.

The criterion for determining whether the aircraft is almost certainly on ground consists in verifying if the coordinates of the aircraft and their time derivatives obey all the following constrains: $|\theta - 8.6^\circ| \leq 20^\circ$, $|\phi| \leq 10^\circ$, $h \leq 5m$, $|v_z| \leq 0.5m/s$ and $v_{gnd} \leq 13m/s$.

4.1 Broken Lever Prediction

The information obtained with the analysis of the degrees of freedom of the aircraft provided a mean of predicting whether or not the lever used in the contact sensor shown in figure 1 is broken. This prediction was made using a finite state machine where the state changes from not broken to broken when during 0.5s the respective lever is not
pressed and the other lever is pressed or the conditions for the aircraft to be almost certainly on ground are met. The state changes back to not broken instantaneously if the lever is pressed.

5 Additional Estimations

The estimation of the state of the aircraft based on the Bayes theorem involved three different predictions. Whether or not the aircraft is on ground given the laser sensor altitude in the same instant, whether or not the aircraft has just landed given the $z$ direction acceleration and whether or not the aircraft has just taken off given the speed of the aircraft.

The goal probabilities must be calculated through the probabilities of the measurement obtained with the sensors, given the occurrence or not of the desired event. The probabilities of the events can then be calculated through the Bayes Theorem using a a priori estimation of the probabilities. This a priori estimation was made according to the probability distribution on the previous instant, being used for filtering purposes. That step is described in section 6.

5.1 Probability of Being on Ground

The probability distribution of the altitude measured by the laser sensor given that the aircraft is on ground was calculated through the evaluation of the probability distribution of the laser sensor measurement while the aircraft is on ground, shown in figure 2, and the probability distribution of the laser sensor measurement given that the aircraft is not on ground was assumed to be a uniform distribution over the complete range of the sensor. The resolution of the laser sensor is $1 \text{cm}$ as shown in 2.

Those probabilities can then be used to compute the probability of the aircraft being on ground through the Bayes theorem. Since this requires an a priori estimation of the state of the aircraft, the probability was calculated directly on the filtering step shown in section 6. In that procedure, an estimation derived from the probability of the aircraft being on ground in the previous instant is used as the a priori estimation, filtering the results of the estimation.

5.2 Landing Probability

The landing probability of the aircraft was calculated through the acceleration measured on the $z$ direction subtracted by an estimation of this acceleration. The estimation took into account the gravity and the centrifugal force. This produced a considerable reduction on the noise during the flight as shown in figure 3, turning the acceleration peaks during the landing more distinguishable. The probability distribution of the acceleration measured on the $z$ direction given that the aircraft has just landed was calculated from the set of measurements performed during real landings shown in figure 4. Analogously, the probability distribution of the acceleration measured in $z$ direction given that the aircraft has not landed was modeled based on a set of acceleration measurements acquired during a flight test. The distribution of the data and the assumed probability distribution are shown in figure 5.

Figure 2: Set of measurements of the laser sensor while the aircraft is on ground.

Figure 3: Acceleration measured in $z$ direction with and its prediction.

Figure 4: Acceleration measured in $z$ direction when the aircraft is landing.

The probability of a landing was then computed considering an a priori probability estimation given by the a rough estimation of the dura-
5.3 Take-off Probability

The takeoff probability could not be measured directly since it does not produce any instantaneous change in the sensors used which can be clearly distinguished from the noise. Nevertheless, an indicator of that probability is mandatory for the success of the estimation based on the Bayes theorem once the direct usage of an a priori probability would mean to ignore completely the fact that the take-off might have different duration at each flight. For that purpose, a prediction was derived from the speed of the airplane. Since a reliable dynamic model for predicting the take-off speed was not available and it was desired that the method could be extended to other aircraft without the need for several flight tests, a simple model was proposed taking only the expected take-off speed into account. The probability of the aircraft having taken off in a given instant was assumed to be given by a sigmoidal function centered in 18 m/s as follows:

\[
P(\text{air}|v_t) = \int_0^v f(v_t|\text{air}, gnd_{t-1})dv = \frac{1}{1 - e^{-\frac{(v-18)}{18}}}
\]  

(2)

Through this probability it is possible to compute the probability of the takeoff given the speed of the aircraft.

\[
f(v_t|\text{air}, gnd_{t-1}) = \left(1 - \frac{1}{1 - e^{-\frac{(v-18)}{18}}}\right) \frac{1}{1 - e^{-\frac{(v-18)}{18}}}
\]  

(3)

The probability distribution of the speed was considered to be uniform, therefore:

\[
f(v|gnd_t) = \frac{P(\text{gnd}|v)f(v)}{P(\text{gnd})} = \frac{P(\text{gnd}|v)}{18}
\]  

(4)

The Bayes theorem can then be used again to estimate the probability of the take-off

\[
P(\text{air}_t|gnd_{t-1}, v_t) = \frac{f(v_t|\text{air}_t, gnd_{t-1})P(\text{air}_t|v_t)}{P(\text{air})}
\]  

(5)

In this case, the a priori estimation of the probability of take-off is considered to be 1 divided by rough estimation of the duration of the take-off.

6 Data Filtering and Partial Data Fusion

The filtering of the data from the probabilities estimators was performed according to three different methods. In the first method, only the probability estimators for the state transitions were considered. In the second method, only the state probability was considered and the transition probabilities were considered to be their a priori values. In the third method, all the probabilities were considered. The use of more than one filtering method intended enhance the robustness against fails in one specific probability prediction, so that the different predictions should produce different outcomes. If a failure occurs in one of the estimators, it is expected that not all the predictors will output the same value.

6.1 Transition Bayes Model

When only the transitions are taken into account, the Bayes Theorem can be used as shown in sections 5.2 and 5.3. The probability of the aircraft being or not on ground is then estimated using the following equations:

\[
P(\text{gnd}_t|\text{data}_{0...t-1}) = P(\text{gnd}_{t-1}|\text{data}_{0...t-1})P(\text{gnd}_t|\text{gnd}_{t-1}) + P(\text{air}_{t-1}|\text{data}_{0...t-1})P(\text{gnd}_t|\text{air}_{t-1})
\]  

(6)

\[
P(\text{air}_t|\text{data}_{0...t-1}) = P(\text{gnd}_{t-1}|\text{data}_{0...t-1})P(\text{air}_t|\text{gnd}_{t-1}) + P(\text{air}_{t-1}|\text{data}_{0...t-1})P(\text{air}_t|\text{air}_{t-1})
\]  

(7)

6.2 State Observation Bayes Model

In the case of a Bayes Model considering only the predictions of the state and not the transitions, the transitions are assumed to be their a priori estimation shown in sections 5.2 and 5.3. The filtering must then be performed in two steps. First, the prediction of the state of the aircraft in the previous instant is used to predict the current state of the aircraft through the a priori transition probabilities. Then, the prediction calculated in the previous step is used as an a priori estimation to calculate the probability of the state in the current instant through the Bayes theorem.

- First Step
7.2 Reliability Layers Approach

The second source of errors in the mode switching comes from unavailable sensors or erroneous information coming from the sensors. Solving this problem, requires the information coming from all sources to be compared and a criteria to be found to give a final result given the information available. Combining all the measures in a single Bayes model in order to provide a final probability distribution is likely to lead to a failure in correcting the errors in a sensor. Making a single set of conditions for considering any wheel or both wheel to be on ground according to the information available, leads to a complex task and the information about the accuracy of the final information is lost.

In order to solve this problem, a model was developed where the estimation is arranged in layers inspired in (Brooks, 1986). Each layer of the model is responsible for making a prediction with a certain degree of certainty and informing whether or not the prediction was possible. The final information made available by the system is whether or not there is any wheel on the ground, whether or not both wheels are on ground and the layer in which this information was achieved, so that it is possible to know how reliable this information is. The following reliability layers were used:

- **Hard Consensus Layer**
  In this layer, it is required that all the sensors are available and all have the same output. The exceptions were that when predicting whether there is any wheel on ground, only one of the lever sensors is required to give an affirmative answer and that the absolute agreement with the analysis of the degrees of freedom was not required. The analysis of the degrees of freedom was only used to indicate contradictions when both criteria disagree with the estimation provided by the other methods.

- **Lever Consensus Layer**
  In this layer, it is required that both lever sensors are available and that the analysis of the degrees of freedom doesn’t contradict the outcome of the lever sensors.

- **Soft Consensus Layer**
  In this layer, it is accepted if one of the levers are broken. In this case, it is required that both criteria of the degrees of freedom was only used to indicate contradictions when both criteria disagree with the estimation provided by the other methods.

- **Best Effort Layer**
  This layer aims to give an answer at any situation, given that there is at least one measurement available. In that case, an error is
not very unlikely to happen. Nevertheless, greater caution is used to state either that both wheels are in ground or that no wheels are on ground. As a result, when an error occur, the outcome is likely to be that there is a single wheel on ground. The aim of this is that the aircraft is set when the state of the aircraft is less certain to the state where the control should be more cautious. In spite of this effort, the both wheels on ground and the no wheels on ground states are not guaranteed also, only less likely to occur mistakenly than the any wheel on ground state.

8 Flight Test

The system implemented was tested during two flight tests in which an accurate prediction of the state of the aircraft was observed. Moreover, it was possible to notice that the mechanical robustness of the contact sensor is good enough for the probability of both sensors breaking in the same flight to be very low. The output of the final prediction on the mode switching algorithm is shown in figures 6 and 7.

9 Conclusion

The main concept used herein to detect the weight-on-wheel is shown in figure 1. The results from the flight tests performed with this sensor showed that the sensor provides a clear distinction between the states where the wheel is or not on ground. Furthermore, the test showed that the sensor is mechanically robust and is not likely to break during a flight and landing. In case one of the sensors breaks, it is very unlikely that the sensor on the other wheel breaks at the same time. Therefore, this sensor already provides a reliable detection of the weight-on-wheel.

Considering the different nature of the signals provided by each prediction source, the possibility of a broken lever was dealt with using more abstract states classifications. One of those classifications informs whether or not both wheels are on ground and the other which informs whether or not there is any wheels on ground. This information is estimated taking into account the results from the weight-on-wheel sensors, the limits for the restricted degrees of freedom on the aircraft while it is on ground and the result from the predictions performed with the Bayes model. The data from all the sources was united through a layered model in which each layer has a set of conditions in which it will provide a classification of the state of the aircraft. If the conditions are not met, the responsibility of providing an answer is transferred to the next layer, which is supposed to have a less rigorous set of restrictions. The results from the flight tests showed that the layer approach provided a correct result for the cases where it was tested.

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References


