Determination of the Optimal Routes for Autonomous Unmanned Aerial Vehicle Under Varying Wind with Using of the Traveling Salesman Problem Algorithm

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Abstract. The goal of this paper is to propose and test the algorithm for traveling salesman problem (TSP) for autonomous unmanned aerial vehicles. In this paper we consider the situation when the multicopter is flying under a variable wind and is intended to visit indicated points. We analyze the efficiency of the algorithm in case of limited flying time on a constant height.

Keywords: Multicopters · UAV · Traveling salesman problem (TSP) · Drone routing problem (DRP)

1 Unmanned Aerial Vehicles

Unmanned Aerial Vehicle also known as drone is a kind of aerial machine. Drones have become one of the symbols of the global fight against terrorism. Nowdays the drones are very popular also in civil purposes. Those machines are used as a flying camera platform, platform for aerial inspection of buildings, bridges and Its hard to imagine that the history of UAV's is that long. Many of a UAVs futures are still under a laboratory experiments and the road to its commercialization and widespread use is still long.

1.1 Unmanned Aerial Vehicles in Military Solutions

The roots of Unmanned Aerial Vehicles (UAV) are strictly connected with the military solutions. One of the first UAVs was the aerial bomber balloon developed and patented in the New York in 1863 by an American inventor named Charles Parley. The idea of this solution was based on a hot-air balloon with a basket filled with explosives. This material was to be dropped on the enemy using a mechanism activated by the clock mechanism. Also, one of the first ideas of an unmanned airplane was strictly connected with army solutions in the war time. In 1916 the first airplane controlled by radio waves

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from the ground was created. Just a few days after the USA officially entered World War I in 1917 the American Army commissioned work on Unmanned Combat Aerial Vehicles (UCAV) [1]. Those first unmanned flying bombs based on biplane airplanes. There were several problems with those first UCAV's. One of the biggest problem was the limited aerodynamic knowledge in those times. It was almost impossible to build well flying unmanned airplane just less than twenty years after the first flight of the Wright Brothers [2] (Fig. 1).

Fig. 1. Kettering Bug one of the first UCAV's from late 1910's (https://upload.wikimedia.org/wikipedia/commons/3/35/Kettering_Bug.jpg).

The period of the 30's and 40's was a time of significant development of the technological potential of the major world powers. One of the achievements of those troubled times is the missile V-1. It is the prototype of the later unmanned airborne vehicles equipped with disposable warheads. Years of the 50's and 60's along with the Cold War between the United States of America and the Union of Soviet Socialist Republics is another period of intensive development of unmanned aerial vehicles in the history. One example is here the American MGM-1 Matador or RGM-6 Regulus I (Fig. 2).

Starting from the 90's of the twentieth century drones (due to the development of electronics and IT) began to increasingly appear more numerous and in the arenas of armed conflict. It is sufficient to mention here the participation of the Israeli-American unmanned aerial vehicles RQ-Pioneer in such operations as "Desert Shield" "Desert Storm", or "UNSOM II".

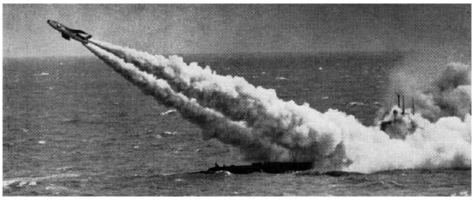

Fig. 2. RGM-6 Regulus I from 1958 (https://commons.wikimedia.org/wiki/File:USS_Tunny_SSG-282_Regulus1_launch_NAN9-58.jpg).

1.2 Unmanned Aerial Vehicles in Non-military Solutions

Today, unmanned flying platforms are becoming increasingly popular due to the significant decline in prices. The use of a no - manned airborne platforms to shoot footage in high quality becomes widespread. Increasingly used unmanned platforms to support a number of projects, such as the inspection of hard to reach places with the use of video cameras and thermal imaging (Fig. 3).

Fig. 3. Thermal image of one of the buildings in General Tadeusz Kościuszko Military Academy of Land Forces

In addition, the no - flying manned platforms begin to be used as robotic couriers carrying parcels. The number of drone applications continues to grow. List of examples of applications of drones is shown below:

- aerial photography
- building inspections
- geodesy and cartography
- delivery of packages
- meteorological measurements
- SAR – “Search and Rescue” actions
- agriculture
- mining
- study of wild life animals
- video transmission

- objects monitoring
- assessment of damages
- archeological discoveries
- emergency medical services

However, the drones are still not fully autonomous platforms capable of independent missions in varying conditions and are far from those which provide laboratories.

1.3 Autonomous Unmanned Aerial Vehicles

There are several types of civil UAV nowadays, but one of the most popular are multicopters. They are stable and easy for steering machines with the ability to hover in the given point of three-dimensional space. There are several types of multicopters but the most popular since to be quadrocopter. That is a multicopter with four vertically oriented propellers. We choose quadrocopters because of its relative low costs and the ability to immediately change the direction of flight (Fig. 4).

Fig. 4. DJI Inspire 1 quadrocopter

2 Drone Routing Problem

Drone routing problem is a variation of Vehicle Routing Problem (VRP). This is well known problem which describe a situation when we need to visit a list of points and we need to determine the optimal path. The optimization may bases on distance, cost or even other criteria. In the case of multicopters determination of the optimum flight path it is extremely important due to the very limited time to operate in the air.

2.1 Determining the Optimal Route

In many situations there is no possibility to control robots in real time. For example, control of a Martian rover must be done with using a class of offline algorithms due to a significant delay due to large distances what must overcome a radio signal from Earth to Mars and back. In addition, autonomous process of robots will need to create more and more new solutions which allows to limit the role of a man in control process. Process of determination of the optimal paths in limited time of drone flight requires a series of calculations. These calculations can be made with using a high performance workstation. That workstation may be located on ground, and path for copter flight may be send to drone with WiFi. On the other hand drones equipped with on-board computers are of considerable Capacity. An example can be DJI Matrice 600 multicopter, which can be equipped with the calculation module with 326 GigaFLOPS onboard. This computer bases on the NVIDIA Tegra K1 quad-core ARM Cortex-A15 processor with 192 GPU cores. Maximal CPU frequency is up to 2.2 GHz Such a large number of floating point operations that may be performed on -board of drone allows to make advanced signal processing from the high resolution camera, analyzing the signals from the sensors in real time. In addition, it is possible to calculate and correct the path through the drone during its flight.

2.2 Determining the Optimal Route in Variable Wind Situation

In this paper we present the method to find a good solution to TSP for modeling UAV (multirotator) vehicle in windy environment. The main deference is that distance of flight that we have to consider depends strongly on direction of flight. Upwind flight is much more expensive in terms of host because UAV have to flight against a wind. Downwind flight is respectively much more cost effective. In light of this TSP solution for UAV have to consider also wind factor.

In this paper we also presented numerical tests for route planning for UAV. By means of computer simulations on benchmarks taken from the TSPLIB we have obtained very promising results using a cluster of personal computers and the MPI library.

2.3 Definition of Problem

The classical traveling salesman problem (TSP) is defined on an undirected graph $G = (V, E)$, where $V = \{1, 2, \ldots, n\}$ is a vertex (cites) set and $E = \{\{i,j\} : i \neq j, i, j \epsilon V\}$ is an edge set. A non-negative cost (distance) matrix C is defined on E. The matrix C is symmetric $(c_{i,j} = c_{j,i}, i,j \in V)$ and satisfies the triangle inequality $(c_{i,j} + c_{i,k} \geq c_{i,k}$ for all $i, j, k \in V)$. The problem deals with finding a minimum length Hamiltonian cycle (a tour that passes through each city exactly once, and returns to the starting city) on a G.

Each feasible solution of the TSP (a cycle including all the nodes of a G) is a permutation of elements of the set V. Let

$$L(\delta) = \sum_{j=1}^{n-1} c_{\delta(j),\delta(j+1)} + c_{\delta(n),\delta(1)} \quad (1)$$

denotes length of traveling salesmen's tour

$$(\delta(1), \delta(2), \ldots, \delta(n), \delta(1)), \delta \epsilon \Pi, \quad (2)$$

where Π is set of all permutations of elements of the set V.

In real environment route planning for UAV have to consider fact that UAV flows with masses of air (wind drag). We have to define ground speed of UAV. When UAV moves down wind speed of vehicle is added to speed of wind and ground speed is relatively higher. When UAV moves up wind speed of vehicle is substracted from speed of wind and ground speed is relatively lower. That means that flight distance is differs $(c_{i,j} \neq c_{j,i}, i,j \in V)$ and matrix C_{wind} is not symmetrical. Let C_{wind} denotes distance matrix in windy environment. C_{wind} can be calculated from C in following way.

Lets assume that matrix W_s denotes wind speed, and element of $w_{i,j}$ of matrix W_s denotes wind speed, on route between cities i and j. Moreover matrix W_α denotes direction (angle of wind), and element of $\alpha_{i,j}$ of matrix W_d denotes wind direction, on route between cities i and j. In light of this we may analyze influence of wind on way between cities i and j. Example situation is presented on figure when we consider downwind flight. We may see that flight time is reduced comparing to windless environment. From perspective of UAV destination city is closer than it is. Speed over the ground is called *ground speed,* speed of UAV relative to ground is called *air speed*.

Similar situation is presented on figure below when vehicle moves upwind (Figs. 5 and 6).

It is also important to note that flight time as well as drag influence depends also on speed of vehicle. More over if speed of wind is higher than speed of vehicle distance is equal to infinity (vehicle can't move that direction).

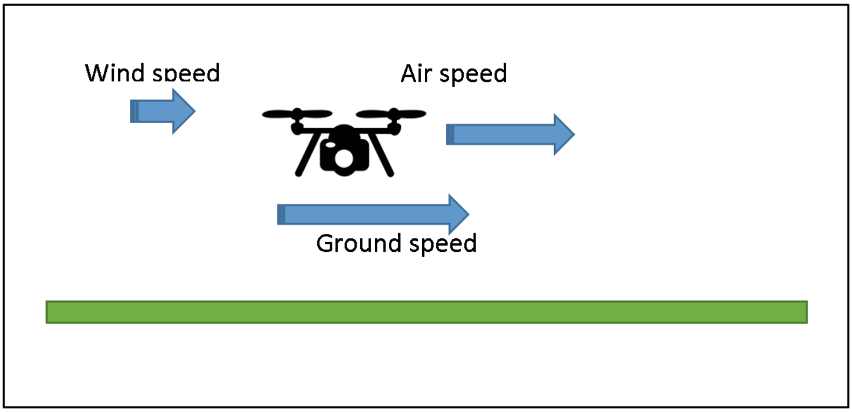

Fig. 5. Analysis of UAV speed in windy environment (downwind flight)

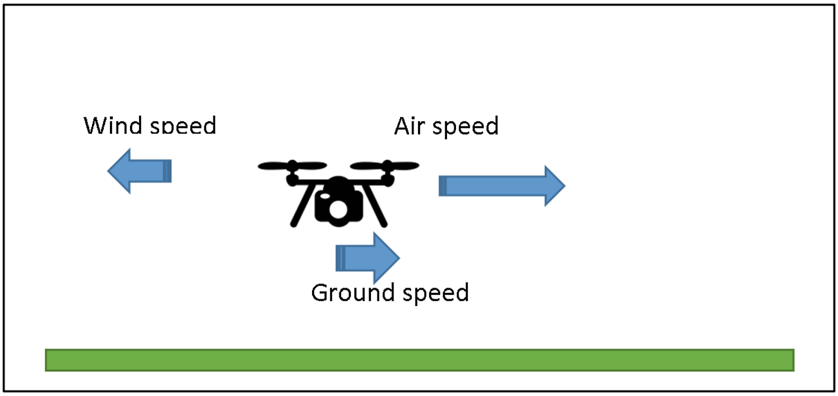

Fig. 6. Analysis od UAV speed in windy environment (up wind flight)

On this basis we are able to calculate new matrix C_{wind} in a following way.

$$c'_{i,j} = \sqrt[2]{\left(c_{i,j} * \cos\left(\alpha_{i,j}\right) + w_{i,j} * \cos\left(\alpha_{i,j}\right) * t_{i,j}\right)^2 + \left(c_{i,j} * \sin\left(\alpha_{i,j}\right) + w_{i,j} * \sin\left(\alpha_{i,j}\right) * t_{i,j}\right)^2} \tag{3}$$

where $t_{i,j}$ denotes flight time between cities i and j.

We may notice that during flight from j to i wind speed is the same but direction is opposite. In light of this new matrix C_{wind} is not symmetrical.

Modification of C matrix to non-symmetrical makes possible usage of almost all know methods for solving TSP problem [3–5]. In this paper we would like to focus on analysis of wind influence on solution of TSP so we decided to use deterministic approach, to find local minimum. For all test cases optimization algorithm is applied (e.g. 2-exchange Lin-Kerninghan algorithm, the so-called “2-opt”) but distance matrix is C_{wind}. In next section experimental results are presented.

In this analysis we have limited our considerations only to a distance analysis. We would like to underline that power consumptions is also very important factor. Drag force depends on velocity second power in light of this flying down wind may reduce power consumption significantly. We plan to extend this model in next steps of research.

3 Experimental Results

We have tested influence of wind on TSPLIB benchmark set. We have analyzed tree situations: no wind, east wind, west wind. We have tested our solution on set of benchmarks with using Lenovo Y50-70 computer with Intel i5 processor and 8 GB RAM under the control of Linux Ubuntu 16.04 operating system. All test cases were solved with 2-opt algorithm [6]. Results are presented below (Table 1).

Table 1. Results

Name of benchmark	Number of cities	Distance		
		Windless	East wind	West wind
kroA100	100	22876	23456	25642
kroA150	150	28996	29012	27805
kroA200	200	33213	33900	33100
kroB100	100	23077	24021	23534

We may have noticed that wind has strong influence on solution. In some cases it extends length by 10 %. And the planed route differs between windless conditions and windy environment.

4 Conclusions

In this paper we proposed and tested the algorithm for traveling salesman problem (TSP) for autonomous unmanned aerial vehicles. We described and tested situations with different vectors of wind speed, air speed and ground speed with using deterministic approach, to find local minimum. For very limited time of flight of multicopters proposed method can allow for autonomous execution of the mission under varying wind. In this paper we represents only the theoretical considerations and its a starting-point for further research.

References

1. Clark, R.M.: Uninhabited Combat Aerial Vehicles: Airpower by the People, for the People, But Not with the People. CADRE Paper No. 8. Air University Press, Maxwell Air Force Base, Montgomery, AL (2000)
2. Howard, F.: Orville and Wilbur: The Story of the Wright Brothers. Hale, London (1988). ISBN 0-7090-3244-7
3. Reinelt, G.: TSPLIB - a traveling salesman problem library. ORSA J. Comput. **3**(4), 376–384 (1991)
4. Papadimitriou, C.H.: The complexity of the Lin-Kernighan heuristic for the traveling salesman problem. SIAM J. Comput. **21**(3), 450–465 (1992)
5. Johnson, D.S., McGeoch, L.A.: The traveling salesman problem: a case study in local optimization. In: Aarts, E.H.L., Lenstra, J.K. (eds.) Local Search in Combinatorial Optimization. Wiley, New York (1997)
6. Englert, M., Röglin, H., Vöcking, B.: Worst case and probabilistic analysis of the 2-Opt algorithm for the TSP. In: Proceedings of the 18th ACM-SIAM Symposium on Discrete Algorithms (SODA), pp. 1295–1304 (2007)