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Cooperation of Unmanned Vehicles

Spolupráce bezpilotních prostředků

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Summary

Cooperation of unmanned vehicles is a key multi-agent application domain. Autonomous unmanned vehicles (UAV) are capable of automated cooperation without needs of a direct user involvement. Application areas of the UAVs operation are rapidly evolving in both military and civil sector. Market available UAV systems usually rely on the human pilot or operator, while the automated flight capabilities are limited to follow manually defined waypoints. The human operator is responsible for the designed trajectory, its safety and detection of potential collisions with another UAVs operating in a shared space. In practical application the operator is able to simultaneously handle only a few number of UAVs.

Multi-agent techniques support coordinated fulfilment of globally defined goals in a UAV mission. Automated goals allocation among available vehicles ensures efficient resources utilization and maximize the mission success rate. Integrated collision detection and avoidance methods with guarantied behavior support the increase of the number of UAVs operating in the mission theatre and allow to increase the system autonomy and thus the efficiency of the overall UAV system. A single operator is capable to operate multiple UAVs with significant increase of the effectiveness and utilization of unmanned aerial assets.

This text introduces a problem of aerial unmanned vehicles cooperation and discuss two main components of cooperative UAV multi-agent system – task and resource allocation in the mission context and cooperative path finding for safe operation in the shared space. A novel mission planning and control system is presented. It provides a flexibility in advanced mission planning and control mechanisms implementation together with an open architecture for out-of-the-box UAV system integration.

Souhrn

Koordinace bezpilotních prostředků je jednou z nejdůležitějších aplikačních domén v oblasti multiagentních systémů. Autonomní bezpilotní prostředky (UAV) jsou schopny automatizované spolupráce bez nutné přímé kontroly uživatelem. Oblasti využití UAV zahrnují rostoucí počet vojenských i civilních aplikací. Běžně dostupné bezpilotní systémy však většinou vyžadují interakci s pilotem, či operátorem. Podpora autonomního letu bezpilotního prostředku je orientována na průlet uživatelem definovaných bodů. Uživatel je však stále zodpovědný za výslednou letovou trasu, její bezpečnost, detekci možných kolizí s ostatními UAV operujícími v dané oblasti a jejich řešení. Při praktickém využití je operátor schopen ovládat jen velmi malé množství bezpilotních prostředků.

Pomocí multiagentních technik jsou prostředky schopny koordinovaně plnit globálně definované cíle mise. Automatické rozdělování cílů mezi dostupné prostředky zajišťuje maximální možné splnění mise a efektivní využití prostředků. Integrovaná detekce a řešení kolizí s garantovanými vlastnosti napomáhá zvýšit počet UAV plnících misi ve stejném prostředí. Vysoká autonomie těchto prostředků tak zvyšuje celkovou efektivitu UAV systému. Jediný operátor je schopen řídit větší množství bezpilotních prostředků a tím zlepšit využití UAV systému a jeho celkovou efektivitu.

V tomto textu se seznámíme s problémem spolupráce bezpilotních prostředků a představíme dvě hlavní komponenty multiagentního systému pro spolupracující UAV – alokaci úkolů a zdrojů v prostředí letecké mise a kooperativní hledání cest podporující bezpečný provoz ve sdíleném letovém prostoru. Seznámíme se s inovativním systémem pro plánování a řízení misí, který umožňuje pružně implementovat pokročilé techniky pro plánování a řízení misí a jeho otevřená architektura podporuje integraci dostupných UAV systémů.

Klíčová slova

Bezpilotní prostředky, plánování a řízení mise, kooperativní hledání cest, spolupráce agentů, alokace úkolů a zdrojů.

Keywords

Unmanned aerial vehicles, mission planning and control, cooperative path finding, cooperative agents, task and resource allocation.

Contents

1. Introduction

The increase of usage of autonomous aerial vehicles (UAV) in the real life situations is an increasing trend that can be seen in everyday life. The most interesting application areas comprise of security operations, border patrol, infrastructure protection, mapping and geo-referenced screening, or precisian agriculture.

In most cases, a UAV is remotely operated by a pilot, which is responsible for the flight safety. An autonomy of such a UAV is reduced to flight towards pre-defined waypoints using on-board autopilot. Human in the loop is needed for both - flight control and sensor processing. For a large unmanned aerial system (UAS), a team of experts is involved in the operation. Such operation teams don't scale well with the number of vehicles; so, a single vehicle is usually used in practical operations (optionally with additional one autonomously navigating into or out of the mission area).

Small UAV systems usually operates in the less restricted airspace similarly to remote controlled (RC) aircrafts. Such operation is restricted by the constraints such as maximal flight altitude, distance from populated areas, etc. In many cases (without special approvals of flight regulation offices) the line of sight between UAV and operator is required during the whole flight, as also an ability to manually overdrive the autonomous control of the UAV. In such conditions the autonomous operation of the team of UAVs is not easily achievable and the commercially available systems are not going beyond these limits.

The operation of multiple UAVs in a shared space needs a trajectory conflict detection and resolution mechanism with guarantied (and certified) behavior to protect UAVs itself, but also other plains and obstacles in the area. Commercially available UAVs has no such mechanism implemented at this moment, but an intensive research on this topic is performed by many universities as well as industrial companies. Legal rules for incorporating UAVs into civilian airspace are under preparation in USA and EU. The plan is to allow the UAVs to share this airspace with manned planes by September 2015 in USA [1] and during 2016 in Europe [2]. This is a significant step towards fully autonomous UAV operations, although the remotely piloted UAVs are mostly taken into account at this moment. One of the biggest legal issue is the responsibility for any potential damage caused by the autonomous UAV operation.

Scientific and technological enablers of the large scale operation of fully autonomous UAV teams in a shared space has to target the reduction of the direct human involvement in the three main areas: (i) mission planning and maintenance, (ii) flight control and (iii) sensor operation. This text provides an overview of the first two issues and shows an example of the modern multiple UAV control systems. The sensor operations are out of the scope of this text.

2. Cooperative Multi-agent Systems

The multi-agent system composed of cooperating mobile agents have to focus not only on mission planning, but also on the spatio-temporal constraints of the operation environment. From the mission point of view the system targets an allocation of tasks to agents, resource sharing, and coordination between agents during the mission execution. A problem of finding a set of non-conflicting trajectories for a number of mobile agents is called cooperative path finding problem [3], which is complex problem, and therefore the state-of-the-art approaches for the cooperative path finding typically rely on some heuristic forward-search technique, where A* is often the algorithm of choice. Both issues are discussed below in detail.

2.1. Task and Resource Allocation

The field of cooperative multi-agent systems relies on research of problem solving and planning in decentralized environments [4]. The integration of the task refinement (decomposition), allocation and local planning enables to explore the planning and allocation possibilities taking into account the availability of resources.

Classical centralized methods depend on one central planning system. Such a system gathers all required input data before the planning process takes place and then the plan is generated using these data. One of the problems of this approach is the need for real-time plan updates based on environments and conditions changes during the mission. On the other hand, in distributed methods of planning, each entity plans its own plan. Cooperation and heading towards common goals is done by various methods of the negotiation.

Distributed planning and problem solving usually refer to environments where planning, solving, or coordination activity is distributed across multiple actors, processes, or sites [5]. Distributed planning has been viewed as either planning for activities and resources allocated among distributed agents, distributed (parallel) computation aimed at plan construction or plan merging activity. There are a lot of problem formulations, frameworks and methods for distributed planning, i.e. [6, 7, 8, 9, 10 or 11]. On the other hand, multi-agent problem solving is more focused on the coordination and interaction of autonomous agents, which is more relevant to the dynamic scenarios.

The multi-agent planning problem is defined as a problem with autonomy of the actors (the agents are at least partially autonomous), locality of the views (no agent has a full global view of the environment, or the system is too complex for an agent to make practical use of such knowledge), and a high degree of decentralization [12].

The multi-agent coordination and negotiation problem is targeted in literature for more than twenty years. The initial work has been dome mainly by Kraus [13] and Osborne [14]. The cooperation of highly dynamic and distributed entities (such as UAVs) forms the need for flexible and loosely coupled architecture. Such an architecture can be found in [5] for a multi-agent cooperation based on task allocation and local resource planning. In this architecture agent interactions are motivated by cooperative solving of a given problem. The agent community tries to find a solution maximizing social welfare [15] similarly to social aspects referred to as comparative advantage in economy [16], where a group of individuals cooperates on the delivery of a service or goods at a lower opportunity cost than other groups. The overall solution cost is minimized using interactions between agents – task allocation, delegation and reallocation, where the allocation of a task to an agent is represented by a social commitment that an agent undertakes [17]. Such a representation provides a powerful tool for task execution stability and performance in dynamic and/or uncertain environments.

An example of the task allocation in a UAV scenario is depicted in Figure 1. There is a set of dynamic resources and a set of required resources for the mission tasks. The multi-agent task and resource allocation provides the mapping of available resources to the required resources according to dynamic constraints (positions, availability and capabilities of the assets) and actual mission needs (the number and type of the tasks, priorities and preferred strategies).

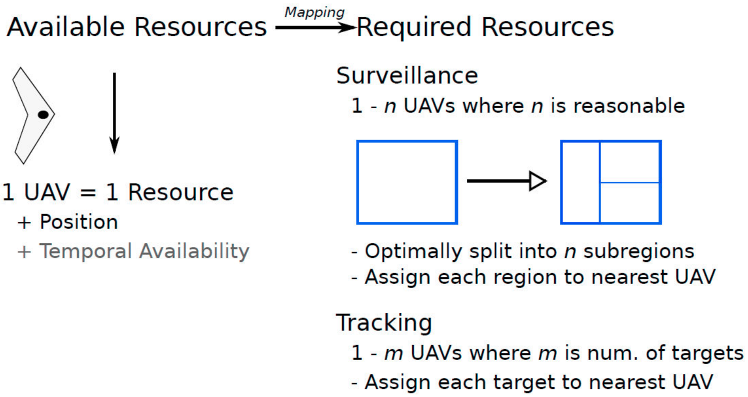

Figure 1: An example of a UAV scenario – the mapping of resources (UAVs) to the mission requirements for surveillance and tracking tasks [18].

The most important dynamic constrain that is often ignored in the classical mission planning systems is spatio-temporal limitation – the trajectories of the plains that fulfil the allocated tasks need to be achievable and collision free. This constrain can be formulated as a cooperative path finding problem discussed in the next section. Based on these foundations, a novel mission planning and control architecture is then presented in Chapter 3.

2.2. Cooperative Path Finding

The cooperative path finding is the problem of collision avoidance for mobile robots, such as aircrafts, i.e. a problem to find a set of non-conflicting trajectories for a number of mobile agents in a shared environment. Each agent has defined starting position and desired destination (or a sequence of destinations) in the environment with (optional) obstacles. For the usual UAV scenarios the environment is relatively sparse in opposite to the classical problem setting with high number of obstacles and agents, but in general, this problem is known to be PSPACE-hard [19]. An illustration of the problem is depicted in Figure 2.

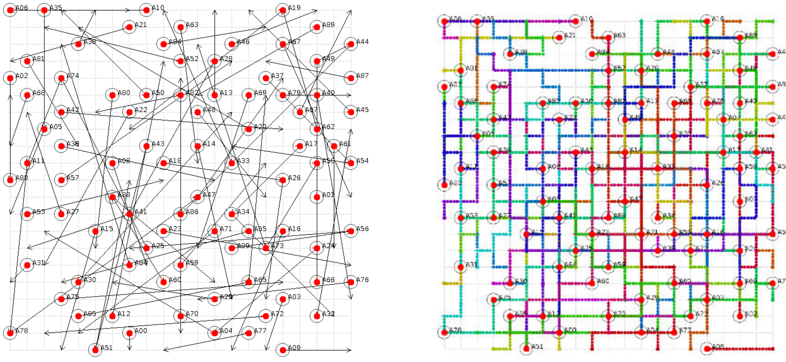

Figure 2: An instance of a random scenario with 90 agents in 2D grid environment. The start and goal positions of each agents are depicted on the left, a solution of the problem is on the right [20].

A solution with guarantied properties can be found by a search of a combined joint state-space, which is Cartesian product of the state spaces (or more general configuration spaces) of all the agents. Such a space is typically searched using some heuristic forward search algorithm, such as A* [21]. The performance of forward search algorithms depends on a low branching factor of the search space, which is in joint-action spaces often exponential in the number of agents. Thus the problem is computationally demanding.

Standley [22] introduced an optimal and complete cooperative path finding solver based on A* heuristic search empowered by independence detection (independent sub problems identification, that is a finding groups of agents that not affect each other) and operator decomposition (joint-actions are decomposed to trees of single-agent actions for a more efficient pruning). This approach has been further extended to an optimal anytime algorithm by Standley and Korf [23]. The algorithm has been originally proposed for agents moving on a grid, but it can be extended to agents moving on a graph as long as the motions of individual agents have identical durations.

Beside the above presented approaches based on optimal forward search, there is also a class of methods for the cooperative path finding, such as Push and Swap [24] or BIBOX [25] that do not target the quality of the solution, but attempt to constructs any feasible multi-agent plan.

The incremental sampling based family of motion planning techniques gained popularity for its ability to quickly find solutions for challenging high-dimensional motion-planning problems. The most well-known class of sampling-based algorithms are the rapidly exploring random trees (RRT) [26] offering probabilistic completeness, but with no guaranties of a solution quality. The variant of this algorithm operating in a joint-state space can be found in [27] or [28].

Karaman and Frazzoli [29] introduced RRT* - a novel sampling-based motion planning algorithm that offers a good scalability to large high-dimensional environments, while at the same time it guarantees asymptotic convergence to an optimal solution. Such approach is able to quickly provide a first solution that is then improved until defined execution time limit. The fast response and incremental quality increase are valuable properties in multi UAV scenarios.

Janovský in [30] introduces an extension of the RRT* applied to multi-agent path planning. The algorithm uses a simulation of reactive collision avoidance method ORCA [31] as a part of the search tree extensions. The algorithm shows a great improvement of instance coverage in limited running time and combines the problem solving capabilities of both reactive and planning technique (i.e., it is able to find solution to instances, where RRT* or ORCA fails due to an environment complexity or a high number of agents).

Another popular approach to solve the cooperative path finding problem is based on discretization techniques for continuous configuration spaces, such as state lattices proposed by Pivtoraiko et al. [32]. It can be used to model dynamics and find feasible paths in wide variety of real-world motion planning problems [33, 34]. The main advantage of the state lattice representation is that it is regular and thus an environment representation can be made implicit.

Asynchronous decentralized prioritized planning for cooperative path finding [20] is suitable in highly dynamic communication restrictive environments. This approach uses no synchronization points during the planning and provides a fast convergence to the feasible problem solution. The strong advantage of this algorithms is its ability to work efficiently even in the dynamic and non-reliable communication environment, where the number of cooperating agents is not static (agents may arrive and leave the scenario) and the communication channels are not stable (i.e., accidental message drop-outs). This approach proved to be reliable in the field-flight experiments [35] and it is a part of the mission control described in the next Chapter. An example of the cooperative paths recorded during the field is depicted in Figure 3.

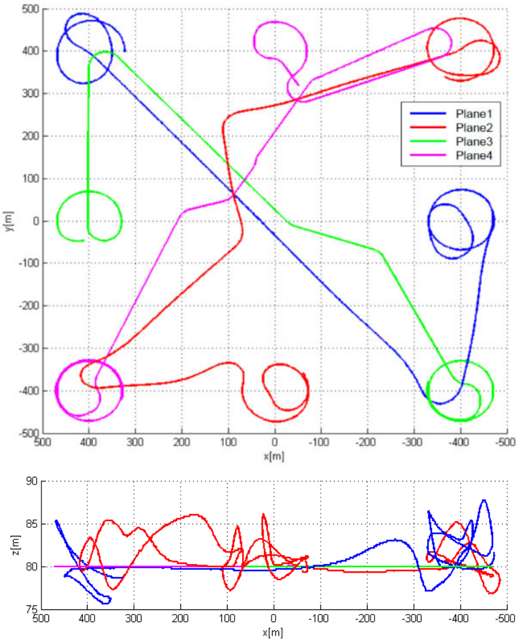

Figure 3: Record of the trajectories of four UAVs in a conflicting scenario, where *x*, *y* is UAV position projected to the ground, *z* corresponds to the altitude of the UAVs [20].

3. Mission Control and Planning

The cooperation of unmanned vehicles can be viewed from two different perspectives. The first one is a coordination of independent self-interested agents in a shared space. This problem is pretty well covered by the solution of the cooperative path finding problem or a various collision avoidance systems [36]. There is a lot of interest in this perspective by both researchers and official authorities because of actual needs for managing the shared civilian airspace. The second perspective goes to the autonomous operation of a set of cooperative UAVs. It is focused on the innovations of the mission control and planning.

Traditionally, the UAV mission consist of limited number (two or three) of plains simultaneously operating in the mission. Moreover, each plain has been controlled by one or more human operators responsible for the flight and sensor operations. The classical operation scheme consist of (offline) mission planning, (manual) allocation of the mission goals to the UAVs, (automated) trajectory planning for each plain with (semi-automated) collision detection and resolution, and (assisted) monitoring of the execution of the mission. On the other hand the requirements for a modern mission control system cover not only in-mission and out-mission automated flight, but also support for coordinated automated flight during the whole campaign. The single-UAV point of view of the classical ground stations is shifted to the mission point of view of the integrated system.

The evolution of such system to the fully integrated autonomous mission control can be powered by the multi-agent task and resource allocation and the cooperative path finding techniques in the closed loop with the execution monitoring. An example of the extended mission control of the open-source Paparazzi system[1] is shown in Figure 4. The system is extended by the dynamic allocation mechanism that reads the actual state of the mission (status of available UAVs, mission tasks achievements, etc.) and provides the dynamic allocation of the task to the available UAVs. The trajectory generation and control of the plains remain on the Paparazzi ground station system [37]. Another example of modern mission control system is Tactical AgentFly experimental system[2], which is further described in the next section.

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[1] Paparazzi, Open-source hardware and software autopilot project is accessible on http://paparazziuav.org

[2] Tactical AgentFly experimental system is accessible on http://agents.fel.cvut.cz/tactical

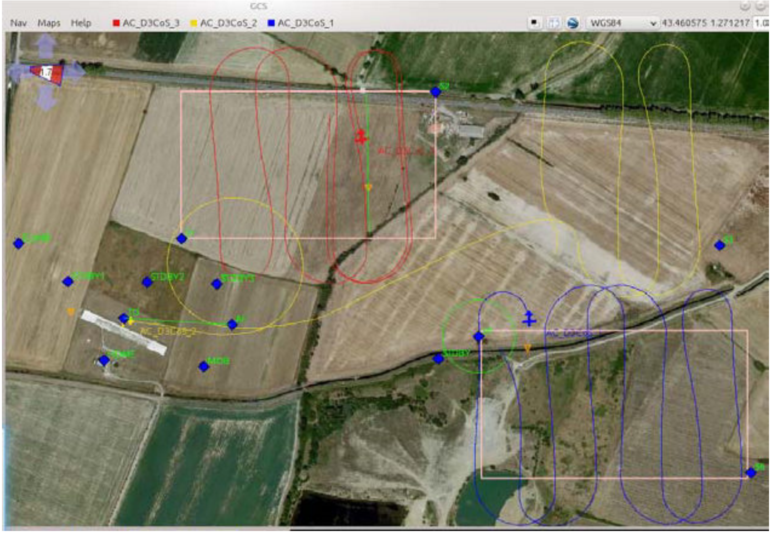

Figure 4: An example of the dynamic mission configuration and updates during execution in Paparazzi autopilot system [37].

3.1. Tactical AgentFly

Tactical AgentFly is an experimental system developed during the series of research projects carried out in Agent Technology Center[3]. During the years, the system grows from the research prototype for validation of multi-agent planning algorithms, coordination techniques and trajectory oriented research to the high maturity cooperative UAV control system ready for the integration with various 3rd party UAV control systems[4].

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[3] Agent Technology Center is a part of Department of Computer Science, Faculty of Electrical Engineering, Czech Technical University in Prague

[4] Four control systems are reported to be integrated – Paparazzi autopilot system (http://paparazziuav.org), MicroPilot (http://www.micropilot.com), ArduPilotMega platform (http://ardupilot.com) and Kestrel Flight System (http://www.lockheedmartin.com/us/products/procerus/kestrel.html).

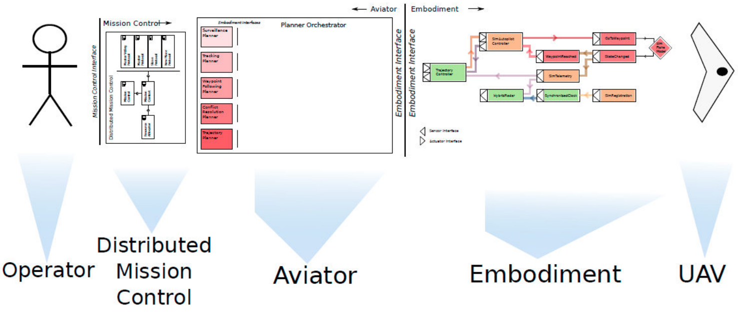


Figure 5: Tactical AgentFly system general scheme.

The main purpose of the system is to test and validate theoretical research achievements in the both simulation and field experiments [38]. The general scheme of the system is illustrated on Figure 5.

The distributed mission control module is responsible for the task and resource allocation based on user input, availability and condition of UAVs. Each UAV is controlled by its Aviator module. It is responsible for planning and monitoring from the perspective of particular UAV and coordination with the others (i.e. cooperative path finding). The key integration component is the Embodiment with standardized Embodiment Interface. It stands for an instance of UAV – simulated or hardware one. It is possible to integrate various implementations of simulated UAVs with different level of detail or existing out-of-the box UAV control system. All of the modules are bi-directly interconnected; so, the command flow propagates from the operator to the UAV in a real-time as an execution monitoring back from the UAV to the mission control and reported to the operator.

The user perspective is represented by the HMI interface. Such HMI provides all the mission information and allows a human operator to interact with the system (mainly the mission tasks definition or manual overdrive of the allocation and planning). The user perspective is depicted in Figure 6. The user experience is the same as with classical UAV control systems.

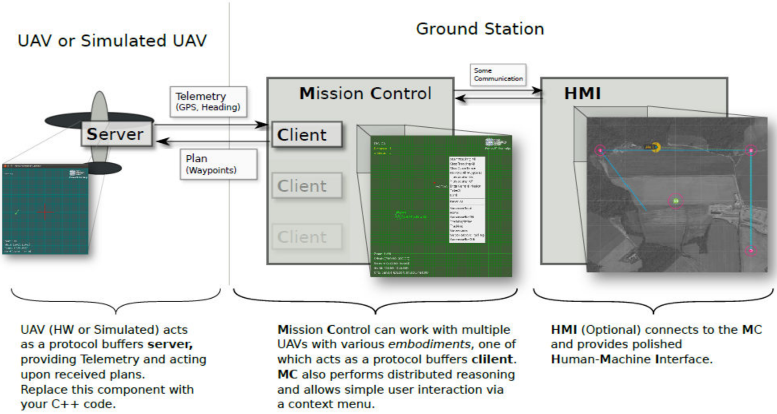
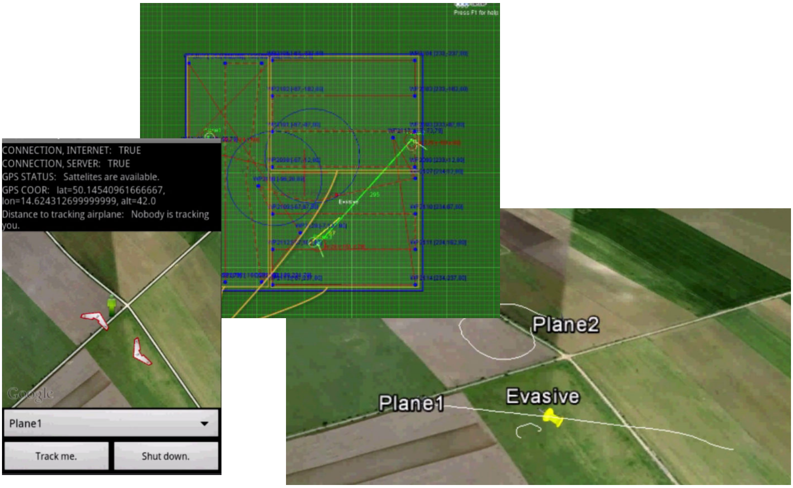


Figure 6: User perspective of the Tactical AgentFly system. It consist of a set of UAVs and a ground station with interactive HMI, mission monitoring screen and mission control software.

The only change is the ground station that is able to effectively control a larger number of UAVs. The intelligent system behind is based on discussed task and resource allocation for dynamic mission control and cooperative path finding ensuring safe operation in the shared space.

The mission control has been originally developed to allow testing and validation of various strategies of multiple UAV cooperation in various scenarios. Thus, the architecture is open to introduce a new mission objectives and (decentralized) algorithms for planning or optimization of the objectives. The system is flexible to cover a large scale of the missions, control strategies, planning algorithms and scenarios. An example of the surveillance scenario combined with tracking is shown in Figure 7. On the left part of the figure a ground unit can ask for an aerial visual support using mobile device (cooperative tracking task). The unit is traversing a controlled area (surveillance task automatically divided to three sectors for three UAVs in the middle of the figure); so, the closest UAVs is re-allocated for the ground unit support while the other two continue to monitor the area (automatically divided to the two sectors).



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CONNECTION, INTERNET:   TRUE
CONNECTION, SERVER:   TRUE
GPS STATUS:   Sattelites are available.
GPS COOR:   lat=50.14540961666667,
lon=14.624312699999999, alt=42.0
Distance to tracking airplane:   Nobody is tracking
you.
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***Figure** 7*: Example of the mission. Left – mobile application with cooperative GPS tracker. Middle – three segments of the surveillance area. Right – record of real-flight trajectories from the field experiment.

Tracking plane gets the highest priority and the other UAVs have to adjust the trajectories to avoid conflicts. The tracking is based on the position monitoring and the strategy for pursuit-evasion game (the record of the trajectories from the field experiment can be seen on the right part of the figure).

4. Conclusion

The aerial unmanned vehicles cooperation is an interesting research topic with many novel application areas. The mission planning and control system capable of autonomous task and resource allocation with integrated cooperative path finding capabilities provides the innovation for the traditional UAV control systems. A single operator is capable to operate multiple UAVs in the shared space with significant increase of the effectiveness and utilization of unmanned aerial system.

5. References

[1] Goyer, R.: Congress to Open U.S. Skies to Drones in Three Years. In *Flying magazine online.* Published: Feb 07, 2012, online at http://www.flyingmag.com/news/congress-open-us-skies-drones-three-years.

[2] Towards a European strategy for the development of civil applications of Remotely Piloted Aircraft Systems (RPAS). *European Commission Working Document*, 2012, online at http://www.uasvision.com/wp-content/uploads/2012/09/EC_SWD_Euro-Strategy-RPAS_120904.pdf

[3] Čáp, M. - Novák, P. - Vokřínek, J. - Pěchouček, M.: Multi-agent RRT*: Sampling-based Cooperative Pathfinding. In *Autonomous Robots and Multirobot Systems (ARMS) Workshop*. 2013, p. 30-46.

[4] Durfee E. H.: Distributed Continual Planning for Unmanned Ground Vehicle Teams. *AI Magazine*. 1999, vol. 20, no. 4, p. 55-61.

[5] Vokřínek, J. - Komenda, A. - Pěchouček, M.: Abstract Architecture for Task oriented Multi-agent Problem Solving. In *IEEE Transactions on Systems, Man, and Cybernetics: Part C*. 2011, vol. 41, no. 1, p. 31-40. ISSN 1094-6977.

[6] Clement, B. J. - Durfee, E. H.: Top-down Search for Coordinating the Hierarchical Plans of Multiple Agents. In *Proceedings of the third annual conference on Autonomous Agents*. 1999, p. 252-259. ISBN: 1-58113-066-X.

[7] Decker, K. - Lesser, V. - Prasad, M. N. - Wagner, T.: MACRON: An Architecture for Multi-agent Cooperative Information Gathering. In *Proccedings of the CIKM-95 Workshop on Intelligent Information Agents*. 1995.

[8] Decker, K. S. - Lesser, V. R.: Generalizing the Partial Global Planning Algorithm. In *International Journal of Intelligent and Cooperative Information Systems*. 1992, vol. 2, no. 2, p. 319-346.

[9] Durfee, E. H. - Lesser, V. R.: Partial Global Planning: A Coordination Framework for Distributed Hypothesis Formation. In *IEEE Transactions on Systems, Man, and Cybernetics*. 1991, vol. 21, no. 5, p. 1167-1183.

[10] Durfee, E. H. - Montgomery, T. A.: Coordination as Distributed Search in a Hierarchical Behavior Space. In *IEEE Transactions on Systems, Man, and Cybernetics*. 1991, vol 26, no. 6, p. 1363-1378.

[11] Erol, K. - Hendler, J. - Nau, D. S.: HTN Planning: Complexity and Expressivity. In *Proceedings of the Twelfth National Conference on Artificial Intelligence.* 1994, p. 1123-1128.

[12] Wooldridge, M.: An Introduction to Multiagent Systems. New York: John Wiley & Sons, 2009. ISBN: 978-0470519462.

[13] Kraus, S. - Sycara, K. - Evenchik, A.: Reaching Agreements Through Argumentation: A Logical Model and Implementation. In *Artificial Intelligence*. 1998, vol. 104, no. 1, p. 1-69.

[14] Osborne, M. J. - Rubinstein, A.: Bargaining and markets. San Diego: Academic press. 1990. ISBN: 0125286325.

[15] Arrow, K. J. - Sen, A. K., - Suzumura,K.: Handbook of Social Choice and Welfare (Handbooks in Economics). Amsterdam: North-Holland, 2002. ISBN: 0444829148.

[16] O'Sullivan, A., Sherin, S. M.: Economics: Principles in Action. Addison Wesley Longman, 2002.

[17] Komenda, A. - Pěchouček, M. - Bíba, J. - Vokřínek, J.: Planning and Re-planning in Multi-actors Scenarios by means of Social Commitments. In *Proceedings of the II International Multiconference on Computer Science and Information Technology*. Piscataway: IEEE, 2008, p. 39-45. ISSN 1896-7094. ISBN 978-83-60810-14-9.

[18] Štolba, M. - Selecký, M. - Meiser, T. - Čáp, M. - Rollo, M. - Komenda, A. - Vokřínek, J. - Pěchouček, M.: AgentFly-In-Air: HW deployment, experimentation and testing of the results from the Tactical AgentFly and AgentScout projects. Technical Report, Czech Technical University in Prague. 2012.

[19] Hopcroft, J. E. - Schwartz, J. T. - Sharir, M.: On the Complexity of Motion Planning for Multiple Independent Objects; PSPACE-Hardness of the "Warehouseman's Problem". In *International Journal of Robotics Research.* 1984, vol. 3, no. 4, p. 76-88.

[20] Čáp, M. - Novák, P. - Selecký, M. - Faigl, J. - Vokřínek, J.: Asynchronous decentralized prioritized planning for coordination in multi-robot system. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2013. ISBN 978-1-4673-6357-0.

[21] Hart, P. E. - Nilsson, N. J. - Raphael, B.: A Formal Basis for the Heuristic Determination of Minimum Cost Paths. In *IEEE Transactions on Systems Science and Cybernetics*. 1968, vol 4, no. 2, p. 100-107.

[22] Standley, T. S.: Finding Optimal Solutions to Cooperative Pathfinding Problems. In *Proceedins of the Twenty -Fourth AAAI Conference on Artificial Intelligence*. 2010, p. 173-178.

[23] Standley, T., - Korf, R.: Complete Algorithms for Cooperative Pathfinding Problems. In *Proceedings of the Twenty-Second international joint conference on Artificial Intelligence*. 2011, p. 668-673. ISBN: 978-1-57735-513-7.

[24] Luna, R. - Bekris, K. E.: Push and Swap: Fast Cooperative Path-finding with Completeness Guarantees. In *Proceedings of the Twenty-Second international joint conference on Artificial Intelligence*. 2011, p. 294-300. ISBN: 978-1-57735-513-7.

[25] Surynek, P.: A Novel Approach to Path Planning for Multiple Robots in Bi-connected Graphs. In *Proceedings of the IEEE International Conference on Robotics and Automation.* 2009, p. 3613-3619. ISBN: 978-1-4244-2788-8.

[26] LaValle, S. M. - Kuffner, J. J.: Randomized kinodynamic planning. In *International Journal of Robotics Research*. 2001, vol. 20, no. 5, p. 378-400.

[27] Kamio, S. - Iba, H.: Random sampling algorithm for multi-agent cooperation planning. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*. IROS, pages 1265–1270, 2005.

[28] Ferguson, D. - Stentz,A.: Anytime rrts. In *EEE/RSJ International Conference on Intelligent Robots and Systems (IROS '06)*, pages 5369 – 5375, 2006.

[29] Karaman, S. - Frazzoli, E.: Sampling-based Algorithms for Optimal Motion Planning. The International Journal of Robotics Research. 2011, vol. 30, no. 7, p. 846-894.

[30] Janovský, P. - Čáp, M. - Vokřínek, J.: Finding coordinated paths for multiple holonomic robots in 2d polygonal environment. In *Proceedings of the 13th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2014)*, pages 1117-1123, 2014.

[31] Van Den Berg, J. – Guy, S. J. - Lin, M. - Manocha, D.: Reciprocal n-body collision avoidance. In *Robotics research.* Springer, pages 3–19. 2011.

[32] Pivtoraiko, M. - Knepper, R. A. - Kelly, A.: Differentially constrained mobile robot motion planning in state lattices. In *Journal of Field Robotics*, 26(3):308–333, 2009.

[33] Ferguson, D. - Howard, T. M. – Likhachev, M.: Motion planning in urban environments: Part ii. In *International Conference on Robotics and Automation*, pages 1070–1076, 2008.

[34] Hwangbo, M. - Kuffner, J. - Kanade, T.: Efficient two-phase 3d motion planning for small fixed-wing uavs. In *Proceedings of the IEEE International Conference on Robotics and Automation*. 2007, p. 1035-1041. ISBN: 1-4244-0601-3.

[35] Selecký, M. - Štolba, M. - Meiser, T. - Čáp, M. - Komenda, A. - Rollo, M. - Vokřínek, J. - Pěchouček, M.: Deployment of multi-agent algorithms for tactical operations on uav hardware (demonstration). In *Proceedings of the 12th international conference on autonomous agents and multiagent systems, AAMAS'13*, 2013.

[36] Šišlák,D. - Volf,P. - Pěchouček,M.: Agent-Based Cooperative Decentralized Airplane-Collision Avoidance. In: *IEEE Transactions on Intelligent Transportation Systems*. 2011, vol. 12, no. 1, p. 36-46. ISSN 1524-9050.

[37] Anh Truong, T.V. - Benda, P. - Vokřínek, J.: The Task Agent Resource Function application in UAV domain. In *AIAA Guidance, Navigation, and Control (GNC) Conference*. Reston, VA: AIAA, 2013, . ISBN 978-1-62410-224-0.

[38] Komenda, A. - Vokřínek, J. - Čáp, M. - Pěchouček, M.: Developing Multiagent Algorithms for Tactical Missions Using Simulation. In *IEEE Intelligent Systems*. 2013, vol. 28, no. 1, p. 42-49. ISSN 1541-1672.

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