Modeling Urban Environments for Communication-Aware UAV Swarm Path Planning

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The presented work introduces a graph based approach to model urban (or otherwise cluttered) environments for UAS utilization beyond line-of-sight as well as out of direct R/F range of the operator's control station. Making the assumption that some *a priori* data of the environment is available, the proposed method uses a classification of obstacles with respect to their impact on UAV motion and R/F communication and generates continuously updateable graphs usable to compute traverseable paths for UAVs while maintaining R/F communication.

Using a simulated urban scenario this work shows that the proposed modeling method allows to find reachable loiter or hover areas for UAVs in order to establish a multi-hop R/F communication link between a primary UAV and its remote operator by utilizing an overlay of motion (Voronoi based) and R/F (visibility based) specific mapping methods.

Abreviations and Nomenclature

GCS	(Ground) Control Station	*MALE*	Medium Altitude Long Endurance
GVD	Generalized Voronoi Diagram	*MAV*	Micro Aerial Vehicle
HALE	High Altitude Long Edurance	*UAS*	Uninhabited Aerial System
LOS	Line of Sight	*UAV*	Uninhabited Aerial Vehicle

VisiLibity	A software package by Obermeyer for visibility related computations.
VRONI	A software package by Held for efficient computation of Voronoi related computations.

I. Introduction and Motivation

Currently many of the smaller tactical scale UAS aim towards high mobility, lower cost, reduced operator personnel and ease of operation. This category of UAVs includes systems like AeroVironment's Raven, EMT's Aladin, or Adaptive Flight's Hornet Micro. As a consequence of these requirements, most of these systems employ a GCS operator who flies the UAV by means of a live onboard video feed and some level of autopilot augmentation. Though higher level control, i.e. the use of preprogrammed waypoints or whole trajectories, is sometimes possible, remote operators often pilot the UAV directly, providing them with immediate sensor data and allowing them to perform tasks such as obstacle detection and classification, collision avoidance, and also path planning.[1] Having the vantage point of first-person-video, the remote pilot can reach a high level of situational awareness, most often not reachable through other means of tele-operation. However, first-person-video also severely limits the number of vehicles in a UAS to essentially the number of remote operators/pilots involved. Increasing the vehicle-to-operator ratio from one-to-several (as, for example, in the larger scale HALE and MALE UAS like Northrop Grumman's Global Hawk or General Atomics' Predator) to several-to-one is an ongoing effort.[2] A major contributing factor is the previously mentioned (shared) situational awareness of the GCS operator(s).

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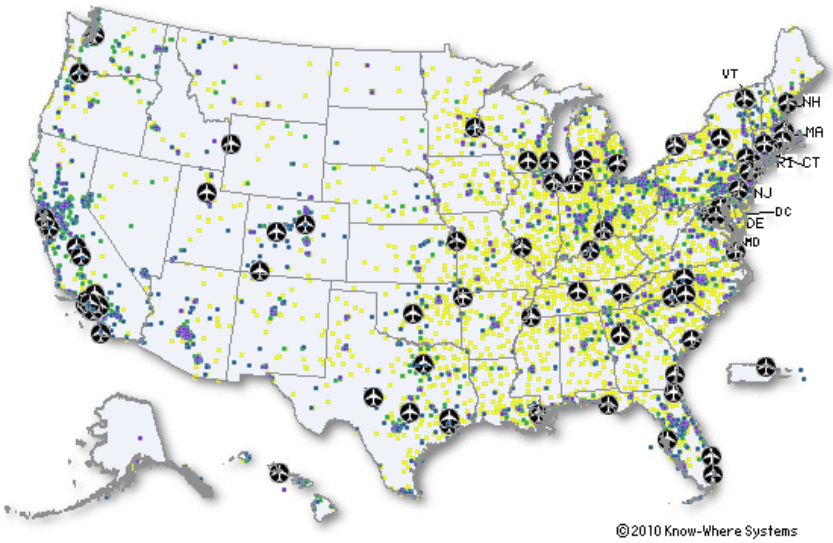
In a UAS with a vehicle-to-operator ratio > 1, full situational awareness of all vehicles at all times can hardly be achieved, if at all sustained. Moving the area of operations into an urban environment only increases the workload on remote pilots by means of more obstacles to detect and avoid, smaller spaces to maneuver in, and tighter constraints on vehicle position and attitude in order to position payload sensors in a useful way - only furtherly complicating the efforts to achieve complete situational awareness.

The research presented in this paper proposes an environment modeling method aimed specifically at UAS which try to combine the advantages of first-person-video remote piloting and the capability increase resulting from the usage of several UAVs simultaneously.

A. UAS in Urban First Responder Scenarios

The authors envision first responders in larger urban areas to have access to tactical UAS to support and coordinate their efforts. The UAS would have several sites strategically distributed throughout the metro area which function as hangars and remote dispatch centers for several UAVs. Regular first responder teams are envisioned to have a dedicated UAS operator attached to them and this operator would join them during any kind of mission. The operator would, once at the scene (or maybe already during the ingress), contact the closest hangar, request access to UAV(s) and utilize the UAV(s) to support the other team members in their mission through the use of the UAV's sensor data.

(a) Urban environments pose motion constraints on tactical UAS on nearly all interesting altitudes. From cars, trees, and light poles all the way up to sky bridges or even FAA controlled airspace. (Image: flickr)



(b) Common high bandwidth data links are not only blocked by mostly all city buildings, but also "jammed" through WiFi Hotspots and other personal R/F usage in open frequency bands. Shown here are only WiFi Hotspots operated by ATT. In urban environments a map showing WiFi sources including private and commercial sources would be much denser. (Image: ATT)

Figure 1. Urban environments pose problems for UAVs on several levels. Physical and other motion constraints pose one kind of obstacle, unpredictable R/F environments render maintaining a high bandwidth data link another major problem.

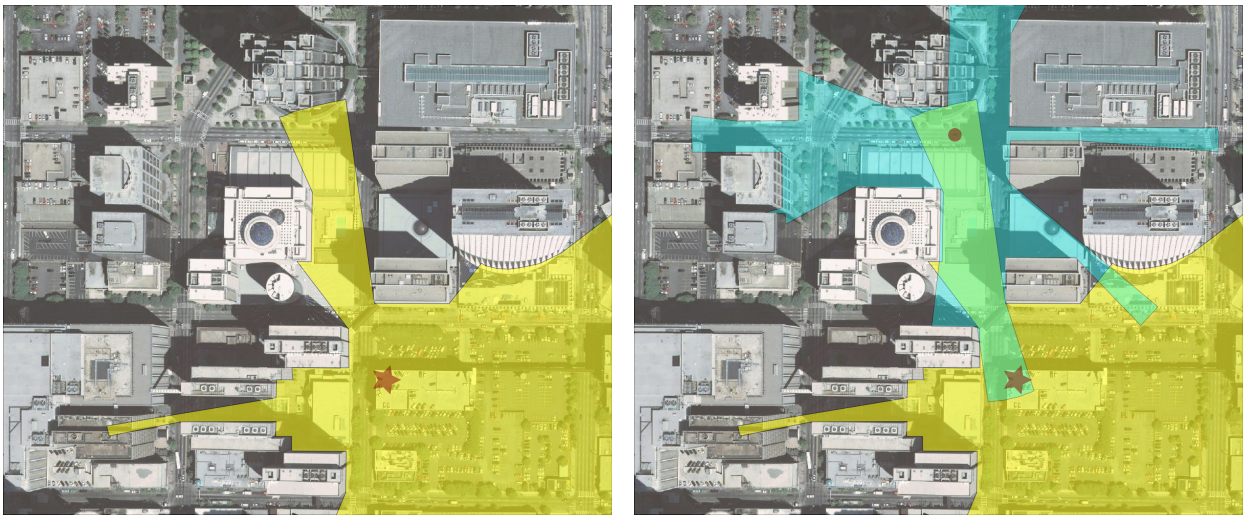
B. Technological Challenges and Scope of this Work

There are several challenges involved in realizing the above envisioned scenario. To limit the scope, this work is mainly interested in a problem related to maintaining a communication or data link between the (deployed) GCS operator and the UAVs operated. Leaving the part of how UAVs initially create a link to the operator for a particular mission for future research, the challenge of interest is maintaining that link.

As indicated in Fig. 1, R/F communication can be complicated in urban environments. Modern buildings not only block most standard R/F, but they also house several other R/F sources which could not only reduce the available bandwidth for the UAS but also potentially render links completely unusable. In order to mitigate adverse effects of buildings, etc., the authors envision the utilization of several UAVs to establish

a multi-hop LOS network between the deployed GCS operator and a primary UAV which would be under full operator control during a given time, giving the operator the first-person-view benefits of enhanced situational awareness in an increased operational area. The designation of being the primary UAV could change during the operation, essentially allowing the deployed GCS operator to switch between the individual UAVs utilized during the mission.[a]

A multi-hop, short-distance LOS R/F network is assumed to provide a robust framework mitigating some adverse effects of an urban environment and hence is intended as a measure to establish a robust communication or data link.[b]



(a) Single-Hop UAS range: GCS operators (located at the star) essentially are limited in the operational area they could position a UAV in by LOS considerations (yellow shaded area).

(b) Multi-Hop UAS range: GCS operators utilizing a UAV as a relay station (located at the circle) have an expanded LOS operational area (yellow and cyan shaded area) without relocating physically.

Figure 2. Introducing UAVs tasked as autonomous relay stations in a multi-hop LOS network structure expands the operational radius of the primary (remotely piloted) UAV while limiting loss of (overall) situational awareness. Given the height of urban high rise buildings, positioning UAVs "high and behind" might not always allow sensor access to the back side of those buildings. Using a relay can mitigate this. (Aerial Image: Google)

However, introducing supportive UAVs (as opposed to the primary UAV under direct operator control) comes at the cost of drastically increased workload. Each additional supportive UAV would require a similar amount of work if it also would be tele-operated, mainly work related to collision avoidance and path planning. For the supportive UAV(s) path planning is furthermore complicated by the dual task of getting from one location to another as well as maintaining LOS to the primary UAV as well as to the GCS or other intermediates.

This work proposes a modeling scheme that should allow supportive UAVs to conduct these tasks without major operator intervention, combining advantages of smaller scale tactical UAS with the benefits of swarm-enabling, higher-level automation in the background.

The principal benefit of a multi-hop scenario is sketched in Fig. 2. The deployed GCS operator still maintains the same operating scheme as if only one UAV would be involved: first-person-view tele-operation. In the envisioned multi UAV scenario an automated system would detect an imminent loss of communication with the primary UAV and automatically (and mainly transparent for the operator) deploy supportive UAVs to act as communication relay stations - effectively maintaining operability of the primary UAV through extended R/F communication coverage. In this scenario the operator maintains a high situational awareness and requires not much additional training. Additional tasks resulting from the increased number of involved

[a]The authors are aware that switching UAVs during tele-operation has adverse effects on the operator's situational awareness, but the switching could be stipulated by a preferred location of a particular UAV or other discriminating factors, like carried equipment, performance considerations, or remaining operational time.

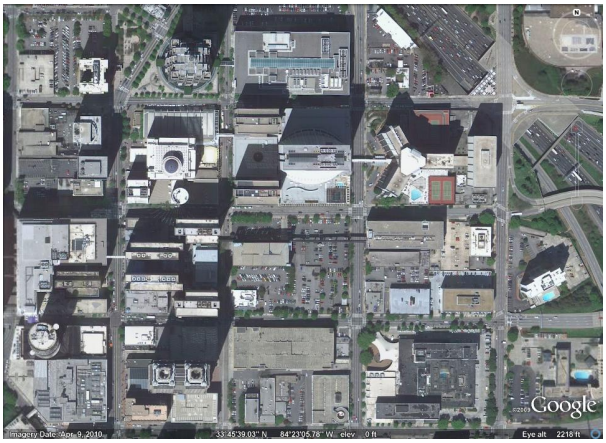
[b]Having a beneficial network topology could be seen as a supportive measure for the physical layer in the seven layer OSI model of computer networking. There exist other techniques throughout the other layers aiming to support robust communication which could be combined with this effort.

UAVs are automated on a higher level and should affect the workload of the operator much less than in a fully operator controlled scenario.

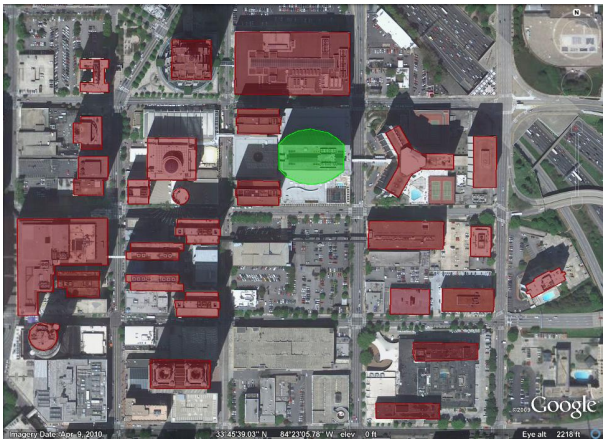
The work presented in this paper aims at supporting first responder UAS through the provision of a specialized method which models an urban environment from separate points of view (motion and R/F), allowing planning algorithms to provide automated guidance for UAVs under special consideration of R/F communication. The particular focus of this paper is the establishment, maintenance, and utilization of mapping methods to allow full automation of the UAVs tasked as supportive R/F relay stations.

II. Modeling Urban Environments for UAV Swarms

Motion planning is intricately connected to the map that is used and there is extensive research on both topics (map generation as well as motion planning), with urban environments being a focus area not only since the DARPA Urban Challenge. In his dissertation,[3] Wooden comments on König and Likhachev[4] by stating that *"optimal planning is outweighed by the need for a "good" plan now."*



(a) Readily available satellite imagery, provided through Google Earth (Image: Google Earth).



(b) Classification of space into *free* and *occupied*. Red overlays could indicate generally occupied space, green could indicate occupied space of interest for the task at hand.

Figure 3. This figure illustrates the extend of the *a priori* knowledge necessary to create the proposed urban environment model. If no 3D model of the city is available, the deployed GCS operator could simply pick an operational altitude and indicate the occupied space on the fly, e.g. during ingress.

The work presented in this paper closely follows this idea by focusing on providing an urban model that would support the usage of UAVs in the scenarios described earlier. Voronoi graphs (the basis for the motion map presented in Sec. B) as well as visibility graphs (the basis for the R/F map presented in Sec. C) have been shown to be of great value and use in the motion planning community. The proposed model combines these two techniques to reduce computational load while coming up with a usable proposition for loiter areas for the supportive UAVs. The proposed model is by no means an optimal approach, just a pragmatic solution that seems feasible and promising for the presented scenarios.

A. Grid and Graph Based Mapping

The (automated) classification of space into the two categories *free* and *occupied* already proves to be challenging - storing the obtained information for later usage by a planning algorithm is another challenge. Jung[5] implemented and evaluated a multi-resolution grid-based static map on a small scale UAV and Cowlagi[6] presents an analysis for an extension of a similar method to dynamic environments. Both proposed methods utilize grids to map, store, and process the environment and both use this grid for planning. At the end, both methods present a path or trajectory for a robot to follow in order for it to go from location A to location B.

Grids and graphs are easily related through cell neighborhood and reachability, i.e. the question whether one can reach cell c_B from cell c_A. This analysis leads to a network of reachable points in space (normally the center of the corresponding cell) and paths connecting these through free cells/space.

The model proposed in this work cuts a lot of corners for the sake of computational simplicity and tries to keep the initial grid-based part as simple as possible, quickly providing a network of paths that could be used to get safely from A to B, reducing the problem of finding a feasible path on a grid based map online to a shortest path problem on an *a priori* computed graph which already represents feasible paths in the environment.

Since the part related to the usage of cells resulting from the grid based map is very minor in this approach, the authors like to think of this approach as graph based (as opposed to grid based), comparing the map (free/occupied grid) to the resulting path (graph of waypoints).

B. Mapping for Motion

In order to allow for such a network of feasible paths to be quickly computed, the number of requirements on such a path generation scheme has to be small. Limiting those requirements to the most fundamental one, collision free motion, generalized Voronoi diagrams (GVD) present themselves as an immediate candidate for 2D scenarios.

Limiting the model to 2D poses no overly constraining limits, particularly if compared to the extra efforts necessary to build a 3D model - keeping in mind that the model will be used by an automated system guiding the supportive UAVs, limiting them to operation in only one plane could even be argued to support the predictability of the system and hence aid the overall situational awareness of the operator. Also, the operational envelope of the (tele-operated) primary UAV is not at all affected through this constraint.

Fig. 3 shows such a 2D slice of the environment. Starting from any kind of aerial footage (like readily available satellite imagery, Fig. 3(a)) the classification of *free* and *occupied* space can be easily accomplished by a person familiar with the area and hence able to quickly judge whether a certain area intersects the operational altitude plane (Fig. 3(b)). The authors assume the *a priori* availability of this classification.[c]

In a future extension this 2D slice could be expanded to be a variable altitude surface in the 3D space or several 2D slices could be stacked in a non-intersecting matter, only connected via special corridors that allow a safe altitude change.

Held's VRONI[8] provides a very fast C algorithm capable of providing Voronoi graphs of polygonal environments (among others). As such, VRONI quickly provides maximum clearance paths through a partially blocked environment. Fig. 4(c) presents a graphical representation of the output of the algorithm. The Voronoi paths could be used as safe trajectories for UAVs to get from a staging area to the position they need to be in in order to fulfill LOS requirements for a R/F connection. In addition to the Voronoi paths (shown separately in Fig. 4(a)), UAVs could also choose to follow the building offsets if that is deemed preferable by a planning algorithm. VRONI also could be used to suggest a staging or loiter area for additional UAVs through the computation of the maximum inscribed circle, i.e. the larges area without any obstructions.

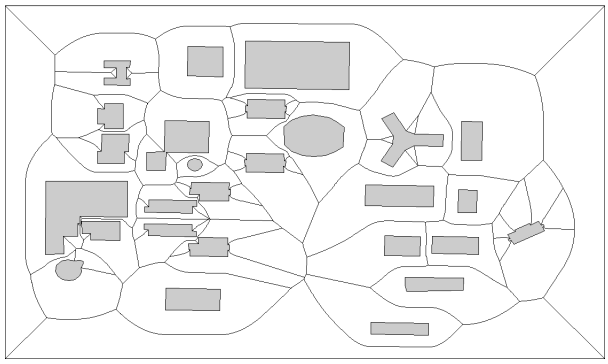
The mathematically correct Voronoi diagram of a polygonal environment contains parts that reach into concave corners of the environment. For the purposes of this work these branches are eliminated (compare Fig. 4(a) to Fig. 4(b)) as the graph essentially provides paths for the autonomous supportive UAVs to follow. Flying into these dead end branches not only results in several path planning challenges[d] but also is deemed unnecessary for the purpose of the modeled scenario as the supportive UAVs are mainly present to allow for a multi-hop LOS connection and the concave section of an obstacle is most likely visible[e] from the root of the branch leading into the concavity.

Summarizing the mapping for motion part, the authors propose a Voronoi graph that is reduced to its cyclic elements as a baseline for autonomous motion. The proposed reduced Voronoi graph provides a dead-end-free network of paths, comparable to a railroad network, that the supportive UAVs are free to use given that other lower level collision avoidance schemes are implemented in order to deal with encounters at graph intersections or situations of oncoming traffic or overtaking.

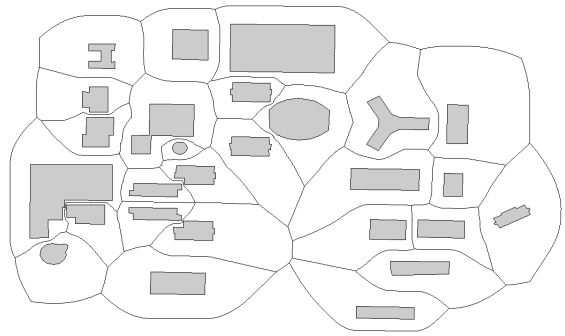
[c]For the purpose if this work this data was provided in the KML format of the Open Geospatial Consortium.[7] Google Earth produces data in this format and was used to generate it.

[d]Dead ends create the problem of obstacle avoidance at the end of the path as well as the challenge of determining when it is safe to turn around - which is particularly of interest for vehicles without turn-on-the-spot capability.

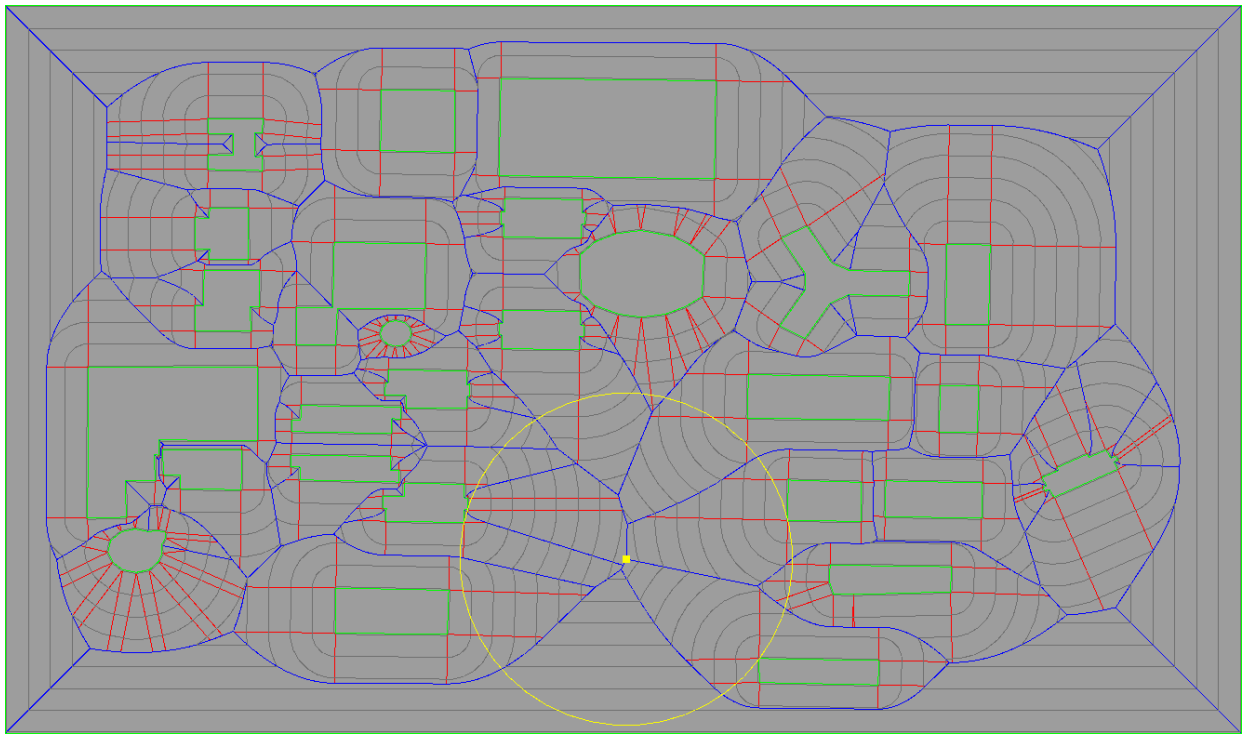
[e]This obviously does not always hold (e.g. spirals), but as the obstacles under consideration are buildings the authors argue that it holds often enough to exclude this special case.



(a) Voronoi maximum clearance paths through the environment. The graph contains leaf nodes extending into concave corners of the environment. For motion planning purposes, these parts are dead ends.



(b) Voronoi graph without leaf nodes, resulting in a purely cyclic graph that segments the environment in one connected cell per obstacle. No dead ends allow for easier usage by non-hover capable aircraft, such as fixed wing MAVs.



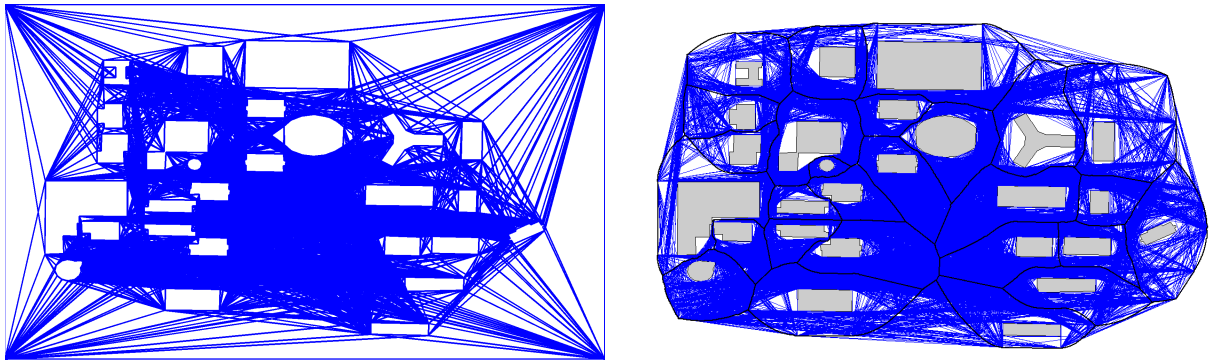
(c) Held's VRONI algorithm provides the backend for the motion map. Shown are the environment/input (green), Voronoi graph (blue), polygon offsets (grey), offset segment indicators (red),and the maximum inscribed circle and it's center (yellow).

Figure 4. Using the GVD the proposed model provides for cyclic paths in order to traverse the environment safely along maximum clearance routes. An online recomputation of this graph is very fast and geometrically beneficial, i.e. truly straight line segments are represented by just two points. This allows for an efficient storage and task dependent resampling into equidistant waypoints (if desired or necessary).

C. Mapping for R/F Communication

The previous section essentially provides UAS with a continuum of safe waypoints along a reduced Voronoi graph. This section elaborates on the selection criteria to select which of these points are actually chosen as target positions for supportive UAVs.

As indicated in Fig. 1, R/F propagation in urban environments can be compromised. This stipulated the choice of constraining R/F paths to range limited LOS paths and as such immediately supports the choice of (reduced) visibility graph based methods.



(a) Complete visibility graph for all vertices of the environment.

(b) Complete visibility graph for some points on the Voronoi graph.

Figure 5. Visibility graphs are used to compute shortest distances between two points by means of visibility (node adjacency) and a measure for the distance (edge weight). If the physical distance edge weigh is replaced by an identical value for all edges, the (physically) shortest path problem becomes the least hops problem.

Obermeyer's VisiLibity[9] library presents a Matlab compatible C++ implementation that can compute visibility graphs, visibility polygons, and graph based shortest paths through an environment. Fig. 5 shows two visibility graphs computed with VisiLibity.

Fig. 5(a) shows a complete visibility graph of the environment. The vertices of the graph represent the corners of the environment polygons. This graph can be utilized to computed (physically) shortest paths between two points in the environment, which is utilized by some path planning algorithms. In the context of the proposed model, visibility graphs are not used for physical motion, but to model R/F propagation. As the supportive UAVs are bound to positions on the Voronoi graph, all R/F transmissions of those vehicles also originate from there. Fig. 5(b) shows a computed visibility graph for some vertices on the reduced Voronoi path, namely the points marking the end of subsegments[f] of the Voronoi graph.

This Voronoi based visibility graph is used as the map for RF propagation. The authors envision this map to be used as indicated in Fig. 6: Given the position of the GCS and the intended position of the primary UAV, potential positions to position secondary UAVs as relay stations can be computed via the visibility graph.

Instead of using a full visibility graph of the Voronoi path, a reduced visibility graph could be used. However, computing the reduced graph is an extra effort, requiring computational resources. The authors have not yet evaluated the overall economics of this, particularly taking into account the necessary recomputations. (Sec. E gives some initial considerations on this.)

As the proposed model does not use the vertices making up the environment to compute the visibility graph, but a set sampled from the continuum making up the Voronoi paths, an immediate dependency gets established. Sec. D elaborates on how this dependency can be used.

D. Combining Motion and R/F Maps into one Urban Environment Model

In order to model an urban environment for the purposes outlined in the described first responder scenarios, considerations other than "just" motion have to be included to establish a complete model of the environment. Other approaches have combined several different methods into one map,[10] the envisioned planner to build upon this work however does not use the two graphs simultaneously, but in sequence.

[f]The subsegments chosen correspond to segments limited by intersections of the Voronoi path (blue in Fig. 4(c)) with either itself or an offset indicator (red in Fig. 4(c)).

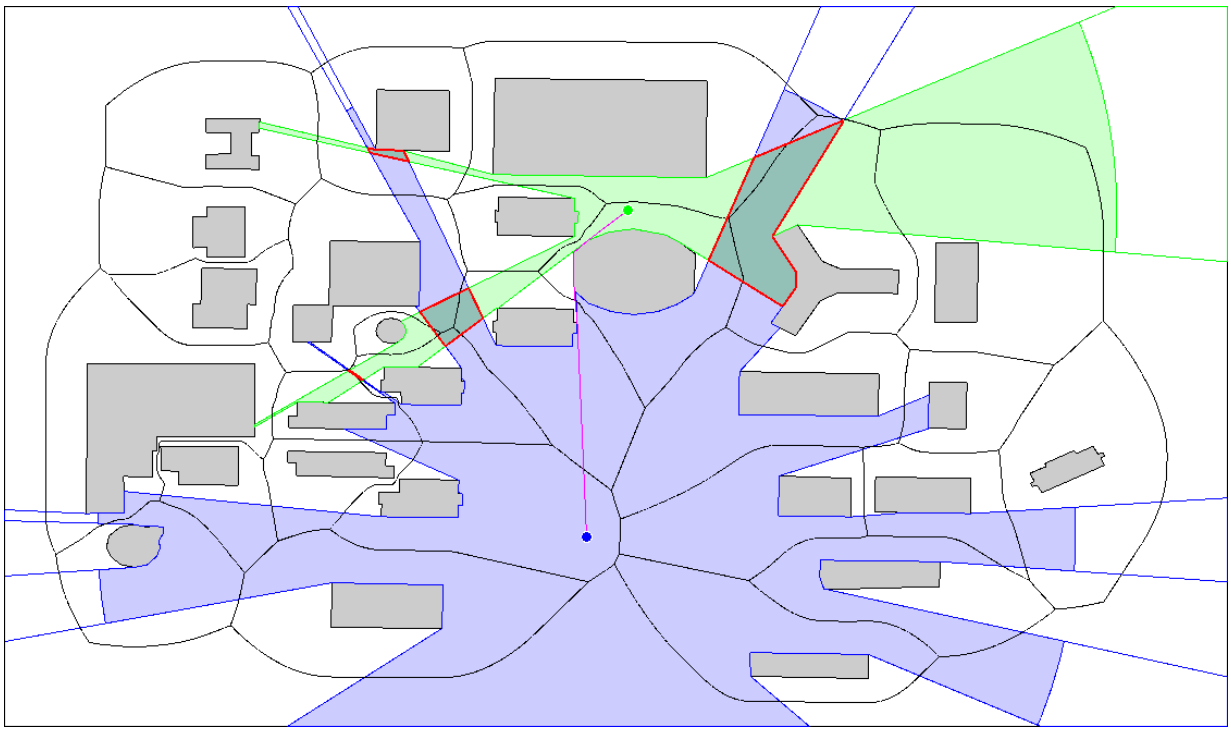


Figure 6. Range limited visibility for two nodes. Assuming that the blue node represents the position of the deployed GCS operator and the green node is the (intended) position of the primary UAV, the intersections (red outline) of the corresponding R/F range polygons describes the areas where supportive UAV(s) have to be located in order to establish a multi-hop LOS R/F link between operator and primary UAV. (Shown also in magenta is the shortest physical path between GCS and UAV.)

Assuming that the classification of the mission environment into *free* and *occupied* space is either *a priori* available are create on the spot by the deployed GCS operator, the UAS can compute the reduced Voronoi graph and distribute it to the involved UAVs. Depending on bandwidth/computational power the UAVs could then either online compute the visibility graph for the Voronoi paths or download it from the GCS. Once the GCS has been established and the area of interest has been indicated (for example a particular building, e.g. as indicated in Fig. 3(b)), the UAS could then use the visibility graph to pre-compute potential loitering locations for supportive UAVs in order to establish a 360° observability of the area of interest and dispatch additional UAVs into the computed staging area (compare to Fig. 4(c)). Once these points (on the Voronoi maximum clearance paths) have been identified, the supportive UAVs could be commanded to those positions.

In the case of a single-hop scenario (as presented in Fig. 6) the visibility can alternatively be used in a more geometric way. Instead of using the obstacles in the environment in order to compute the visibility between nodes representing a somehow sampled Voronoi path, the node positions of the GCS and the primary UAV together with the environment vertices can be used to compute a visibility polygon. In a single-hop scenario the intersection of these two polygons represents the area(s) in which supportive UAVs have to loiter in order to establish a LOS link with one relay point. A subsequent intersection of these areas with the Voronoi paths generates all points on the Voronoi graph that could be used to establish the link. This method seems specifically beneficial for future robustness considerations,[11] however it fails for multi-hop scenarios with several actively relaying supportive UAVs.

In cases where this polygon intersection fails or is expected to fail (i.e. multi-hop scenarios), the Voronoi paths could be sampled in a matter such that the Voronoi path enclosing the area of interest (compare to Fig. 3(b)) is sampled at a higher resolution. Using the resulting vertices the minimal set of supportive UAV loiter positions could be computed to completely cover the cell corresponding to the area of interest, effectively establishing a perimeter that allows the (R/F) constraint free motion of the primary UAV and the deployed GCS operator in the vicinity of the area of interest.

As soon as the deployed GCS operator starts to teleoperate one of the UAVs (declaring it the primary UAV), the automation could use the visibility graph to predict and estimate the LOS R/F link and command supportive UAV along the Voronoi path in a fashion maintaining a constant communication link between the deployed GCS operator and the primary UAV.

E. Dynamic Mapping

As stated in the introduction to the problem, the scenario assumes some initial knowledge of the environment, such as a rough (3D) outline of major buildings in the area of interest. As the first responders perform their mission, the GCS operator essentially performs a more detailed exploration of that particular subsection of the environment and the need could arise to update the *a priori* available environment information. Assuming that the GCS interface allows for an easy entering of changes in the environment during the mission which does not increase the workload of the operator beyond an infeasibility threshold, those changes could also render the UAS nonoperational due to the computational load this change in the environment causes.

Held's VRONI algorithm is a highly optimized code and originated in numerical geometry. During the authors' initial experimentation with the Google Earth interface and the resulting frequent changes in the represented environment, VRONI has always terminated in essentially negligible time scales (< 10 ms), which matches the estimated runtime[8] of $0.01n \log_2(n)$ ms for n line segments. In these cases a full recomputation of the complete environment was performed, not using VRONI's methods to insert or delete features to an existing graph. The authors believe that in a future implementation into a UAS VRONI is by no means expected to be a computational bottleneck.

The computation of the visibility graph (using Obermeyer's VisiLibity library) in comparison takes a much longer time. Obermeyer states[g] that the currently implemented method compares to a complexity of $O(n^3)$ and that faster algorithms on the order of $O(n^2)$ are known. However, Obermeyer states that this performance drawback is caused by a desire for code reusability and could be corrected in future versions of the library. Besides the necessary full recomputations resulting from changes in the environment (which cause not only changes in the placement of sight blocking obstacles but also, through the altered Voronoi graph, in the location of the tested vertices), the visibility graph has to be constantly recomputed whenever

[g]VisiLibity sources or documentation, e.g. `http://motion.mee.ucsb.edu/~karl/VisiLibity/doxygen_html/class_visi_libity_1_1_visibility___graph.html` (checked July 2010).

the deployed GCS operator and the primary UAV are moving. However, the authors believe that a noticeable improvement in computation time can be achieved by slight modifications. In the currently implemented version the visibility graph is completely recomputed for every change of GCS or primary UAV. However, with the exception of these two nodes (and under the assumption of an unchanging environment) the part of the graph created for positions on the Voronoi path are static. Expanding the adjacency matrix of this core part by two for the the GCS and primary UAV and just computing the (undirected) visibility of those two nodes to all the other nodes on the core part should trim down computational requirements.

Though the visibility graph proves beneficial in order to estimate R/F connectivity, there is an inherent mismatch between the discrete vertices of this graph (which can be interpreted as waypoints for the supportive UAVs) and the continuum of possible positions the supportive UAVs could actually be commanded to along the Voronoi paths. Looking at Fig. 5(b), it becomes obvious that this continuum has been limited to a subset of points along these paths.[h] In order to make a better prediction of R/F visibility the number of nodes would have to be increased, however the computational complexity of $O(n^3)$ quickly renders higher node numbers unusable for online implementation.

There are several potential ways to mitigate this effect. Assuming that an initial link has been established the algorithm could make use of the fact that the primary UAV is most likely not to jump through space[i] and increase the node density in areas deemed relevant, e.g. in the vicinity of the primary UAV, the GCS, as well as the actively relaying supportive UAV(s). Since the Voronoi path can be easily resampled along its subsegments, this approach seems feasible. Also, the proposed methods in Sec. D could be used to reduce the number of vertices for visibility computation, resulting in a multi-resolution visibility graph with more nodes closer to the regions deemed to be of interest.

F. Completeness of the Map

The authors believe the proposed model to be complete for the envisioned scenarios. Given the scenarios the deployed GCS operator is assumed to be embedded into groups of regular first responders, resulting in a relative proximity of the operator and the area of interest (e.g. a particular building). Given the relative position of the operator and the primary UAV in close proximity of the area of interest, a dual-hop scenario (i.e. the usage of two intermediaries) is believed to cover the vast majority of all cases, if not a single-hop scenario suffices. This gives rise to the assumption that a future planner could either use the visibility polygon intersection method or the relay perimeter around the area of interest.

III. Related Issues and Future Work

This section will briefly introduce related and future work in context with the proposed model. It aims at completing the overall picture of the problem and will expose the urban environment modelling through the proposed mapping technique as a vital piece in the puzzle.

A. Path Planning

Having the combined Voronoi/Visibility map, the autonomous selection of the loitering areas and the path planning on how to get there is another challenge. Two methods have been identified for a more detailed future study (the intersecting polygon method as well as the static perimeteter method). Solving the selection problem in a distributed manner with several requirements to be fulfilled at the same time (e.g. on link metrics, maximum distance traveled, safety of loitering areas, etc.) poses another challenge.

B. GCS Layout and Interface Design

One of the overall goals of this effort is to minimize the extra workload[12] on the operator necessary to allow for the introduction of autonomous relay UAVs. However, even if the path planning is solved, there is an underlying requirement for an accurate map that has sufficient detail. As the GCS operator controls the primary UAV mainly by remotely piloting it, on one hand the operator is not too concerned about

[h] In Fig. 5(b) the utilized points represent the start and end points of subsegments of the Voronoi graph - resulting in a higher node density in areas of higher curvature.

[i] However, the case in which the operator chooses to utilize a different UAV as the currently used one, from an algorithmic point of view this essentially is such a case.

mismatches of the map and the real environment as the UAV is essentially under manual guidance. On the other hand, the planner for the autonomous relay UAVs needs an accurate map for a proper collision free operation, hence resulting in the need to keep track of mismatches and update them (preferably) on the fly as the operator encounters them. This, however, is an extra burden on the operator and adds to the overall workload. As stated several times in the description of the first responder scenarios, the GCS also will have to be easy and efficient to use to completely generate the initial *free/occupied* classification. Research is necessary to look into how to minimize the impact of that through smart GCS and interface design.

C. Task and Role Allocation in (Non-)Homogeneous Swarms

Utilizing the proposed mapping method supports the utilization of swarms of UAVs for first responder operations. Having essentially increased the available distributed payload capacity over the swarm (assuming homogeneous airframes for primary and relay UAVs), the authors are interested in how to utilize different sensors carried by different vehicles. Challenges are how to switch the primary UAV, how to distribute the relay UAVs given the added functionality as alternate or backup sensors, how to deal with losses of UAVs during mission time, and how all of that impacts operator performance.[13,14]

D. Mobile Ad-Hoc Networks

Even given that the relay UAVs establish a configuration that allows multi-hop LOS communication between the GCS and the primary UAV, the underlying network implementation has to support these changing network topologies. Ongoing research deals with algorithms which optimize routing, throughput, and latency for these scenarios, however, there also already exist several ready-to-use implementations. The authors intend to revistid earlier resarch[15,16] and apply the findings to the overall UAS architecture.

IV. Conclusion

This work proposed a method to model an urban environment for usage by future UAV supported first responders. The method balances the need for safe motion and a stable R/F link through the introduction of two different maps, one for motion, one for R/F linkage estimation. Future planners are envisioned to itarively use these two maps in order to guide supportive UAVs to positions beneficial to the mission completion while minimizing operator intervention and workload increase.

The proposed method is not claimed to be optimal in any sense, but a purely pragmatic approach to a problem at hand.

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