

**Towards Autonomous Drone-Based Dynamic and Seismic Response  
Monitoring of Bridges**

**Quarterly Progress Report  
For the period ending December 1, 2021**

Submitted by:

PI- Mohamed Moustafa

Post-doctoral Researchers - Luna Ngelajaratan and Ecem Bas

Graduate Student – Munni Banik

**Department of Civil and Environmental Engineering  
University of Nevada, Reno**



ACCELERATED BRIDGE CONSTRUCTION  
UNIVERSITY TRANSPORTATION CENTER

Submitted to:

ABC-UTC

Florida International University

Miami, FL

January 2022

## **1. PROJECT ABSTRACT**

There has been increasing interest and use of unmanned aerial vehicles (UAVs), especially in the past decade, for infrastructure inspection. The goal of this study is to extend the use of UAVs to a new application in the area of infrastructures rapid assessment under service conditions and extreme events such as earthquakes. The project will leverage several well-established technologies such as autonomous UAVs systems along with extensive expertise in vision-based monitoring of infrastructure systems like bridges. Our objective is two-fold: (1) extend the use of video cameras and principles of digital image correlation and target-tracking to UAV systems for dynamic displacement measurements and monitoring; and (2) provide foundational work towards establishing a framework that benefits from early warning systems to launch UAVs and collect vibration videos to use for near real-time post-disaster assessment of infrastructure systems and rapid decision making. We will focus on earthquakes, but the results from the project could be generalized in the future and extended to other extreme events. This project will provide unique testbeds in the Earthquake Engineering Laboratory at the University of Nevada, Reno where UAVs will be used to monitor online shake table tests, and results from the monitoring will be used in establishing the future infrastructure assessment framework.

## **2. RESEARCH PLAN**

### **2.1. STATEMENT OF PROBLEM**

The status of our aging infrastructure in the US or elsewhere around the world has been recently one of the biggest challenges facing governments and decision-makers. Maintaining, repairing, or replacing existing infrastructure systems is a major undertaken activity in the US and around the world. Nonetheless, there is a dire need to have a forward look at future and next-generation infrastructure systems. In the US, the ASCE has laid three pillars for solving the nation's infrastructure problems, i.e. (a) strategic and sustained investment, (b) bold leadership and thoughtful planning, and (c) careful preparation for the needs of the future. A major component of the ASCE's "Preparing for the Future" vision is to utilize emerging technologies to ensure infrastructure resilience in the face of extreme events and develop processes that modernize and extend the life of infrastructure, expedite repairs or replacement, and promote cost savings. The innovative applications of emerging technologies in infrastructure assessment and structural health monitoring has shaped several research thrusts among the civil and structural engineering communities and is one of the key motives of this proposed study.

Several global technologies are on the rise such as aerial robotics, which are commonly referred to as unmanned aerial systems (UAS) or unmanned aerial vehicles (UAVs), or simply "drones". Many of the critical lifelines and infrastructure systems such as bridge networks or power grids and transmission lines have taken serious steps towards adopting UAVs for regular maintenance and inspection. In fact, the federal National Cooperative Highway Research Program (NCHRP) has recently solicited research proposals for "Evaluating and Implementing UAS into Bridge Management Methods Through Element-Level Data Collection". Further using bridges as one example of critical infrastructure systems, we find that a large deal of research studies has been sponsored, mostly through various Departments of Transportation (DOTs), to use UAVs for visual bridge inspections. However, none of the ongoing or emerging efforts have properly considered the use of UAVs for dynamic vibration and structural system identification of bridges or other infrastructure systems, nor considered real-time or near real-time structural assessment in the case

of extreme events such as earthquakes. Future applications of UAVs to rapidly inform post-disaster decisions such as assessing a bridge condition to open it for traffic or not would be of great importance, which is the specific motivation of this proposal.

## **2.2. RESEARCH APPROACH AND OBJECTIVES**

Our specific objectives are: (1) validate and verify (V&V) the use of UAVs videos along with principles of digital image correlation (DIC) and target-tracking for dynamic displacement measurements and structural health monitoring (SHM); and (2) provide foundational work, towards establishing a future autonomous assessment framework, such as exploring target-based and targetless UAVs vibration monitoring, or exploring feasibility of two- vs. three-dimensional (2D vs. 3D) and one vs. two UAVs-based measurements if budget and time allows. Thus, it is important to note that the main developments sought in this study will be in the algorithms and methods in video processing and structural assessment. Developing new algorithms for UAVs path finding or seismically-triggered launch systems is not part of the scope for instance, but rather commercial auto-pilot or autonomous navigation systems will be used to prove or demonstrate the concept. Once the viability of UAVs dynamic and seismic monitoring solutions is demonstrated through this project and further knowledge gaps are identified from the synthesis of available technologies, future multi-disciplinary efforts, through a second year extension of this project for instance, could leverage expertise from computer science, robotics, civil engineering, etc. to optimize or enhance the UAVs triggering, launching, navigation, and data transfer within the envisioned framework.

To accomplish the above objectives, the PI will leverage extensive expertise in vision-based dynamic response and seismic monitoring of infrastructure systems like bridges. We will provide unique testbeds in the Earthquake Engineering Laboratory at the University of Nevada, Reno where UAVs will be used to monitor online shake table tests, and results from the monitoring will be used in establishing the future infrastructure assessment framework as explained in the work plan section. Examples of our previous work that will be further extended in this study focused on vision-based target-tracking measurement errors, demonstrating large-scale and field monitoring of bridges, and tackling image and signal processing challenges. Fig. 1 provides some of the vision-based monitoring applications conducted by our team including a recent unique full-scale building test at world largest shake table in Japan through an NSF-funded US-Japan collaboration (Fig. 1b). Most of the work so far has used stationary cameras, but we are recently extending many of our established concepts and developed tools to UAV-based video monitoring (Fig. 1d).



**Fig. 1** Sample of vision-based monitoring of large-scale seismic tests and SHM field applications

### 2.2.1. SUMMARY OF PROJECT ACTIVITIES

An experimental approach will be used and several research activities will be executed to accomplish the objective of this study. A summary of the proposed research tasks is as follows:

- Task 1 – Synthesis of existing methods and technologies towards building a fully or semi-autonomous UAV-based infrastructure dynamic response monitoring and assessment framework
- Task 2 – UAV-based displacement measurement accuracy (V&V tests)
- Task 3 – Large-scale seismic monitoring test framework validation
- Task 4 – Summarize the results in a final report

### 2.2.2. PROGRESS OF RESEARCH TASKS

An overview of each research task and progress-to-date is presented in this section.

#### **Task 1 – Synthesis of existing methods and technologies towards building a fully or semi-autonomous UAV-based infrastructure dynamic response monitoring and assessment framework**

Our ultimate goal from this project is to provide foundational work and outline future needs towards establishing a successful fully or semi-autonomous UAV-based infrastructure dynamic response monitoring and assessment or inspection framework, which can be employed under service conditions or extreme events such as earthquakes. The objective of the first task of this project, which emerged to be the main task of this project because of the challenges faced in testing in tasks 2 and 3, is to identify the pieces and components that need to be integrated to achieve such framework. An overview of the work underway is presented in Appendix A.

## Task 2 – UAV-based displacement measurement accuracy (V&V tests)

A wide-range of methods will be surveyed and synthesized for the various components of the envisioned assessment framework. In this task, we will conduct two sets of V&V tests for UAV static and dynamic displacement measurement accuracy to understand the limitations and potential of hardware effectiveness and control (e.g. gimbals versus UAV motion correction) and post-processing methods. For the two sets of tests, we will additionally explore target-based and targetless UAVs vibration and displacement monitoring, and ideally if budget and time allows, the feasibility of 2D (using one UAV) versus 3D (using two spatially correlated UAVs) measurements. The first set of tests will use the static V&V test previously devised by our research group to measure tracking points displacements against the standard one-inch block. The second set of tests will be more elaborate and consider both static and dynamic motion of a rigid small-scale tower on a shake table as shown in Fig. 2. The sought V&V tests in this task are expected to properly quantify both static and dynamic UAV-based displacement measurements, which has not been comprehensively done yet.



**Fig. 2** – Example of a V&V test for drone-based dynamic response monitoring.

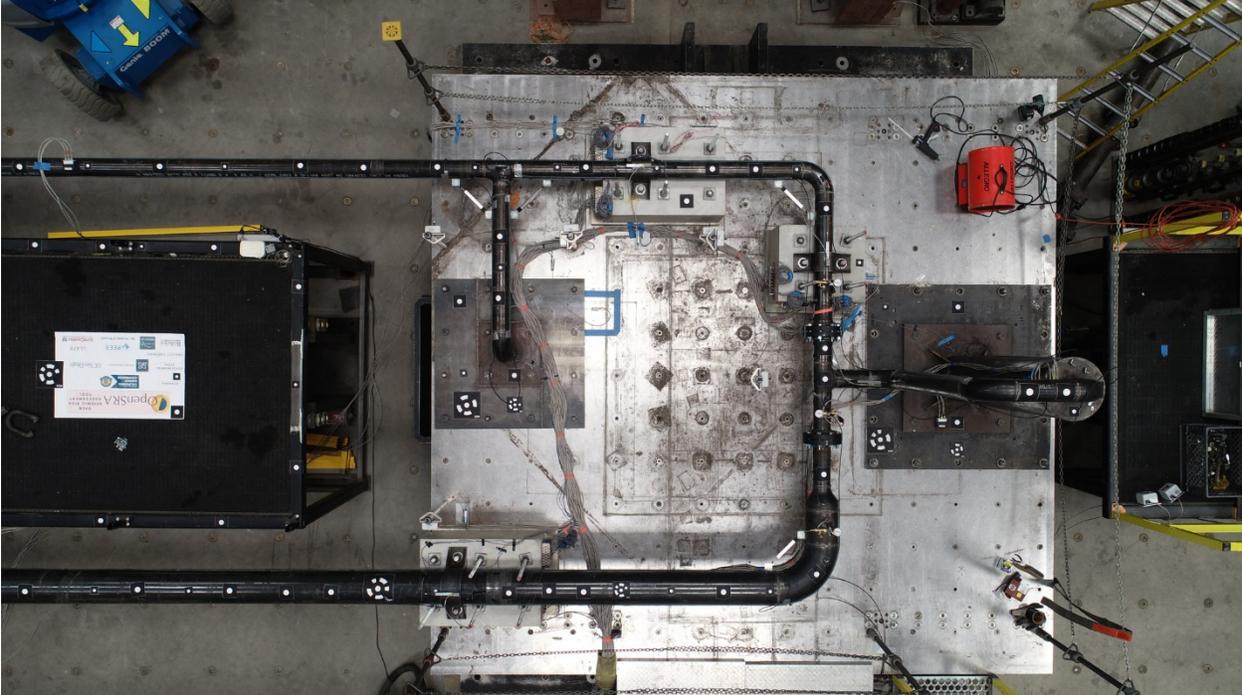
## Task 3 – Large-scale seismic monitoring test framework validation.

The objective of this task is to investigate the viability and/or demonstrate UAV-monitoring as part of a full integrated system using at least one large-scale shake table test to be conducted at the Earthquake Engineering Laboratory at UNR. As mentioned before, the PI has been conducting and monitoring several large-scale single or multiple shake table tests over the past few years. In this task, we have already “piggybacked” a full-scale test in Summer 2021 for a natural gas pipeline system (representative large-scale infrastructure system) that was tested using two shake tables at UNR. Figure 3 shows the test setup and Figure 4 shows sample picture collected by the drone for the vibrating system. It is again noted that the purpose of these tests is to validate for the first time

the tracking algorithms used in UAV-based dynamic response monitoring systems. Thus, only exploratory results will be provided from this major and exclusive task to conclude this phase of the project.



**Fig. 3** – Multiple shake table test setup for an infrastructure system monitored by drone at UNR.



**Fig. 4** – Sample picture collected by hovering drone for the tested infrastructure system.

## TASK 4 – Results dissemination and Final report

A final report will be prepared and submitted for wide dissemination through the ABC-UTC. The report will be complemented with ABC-UTC guide for the roadmap of future implementation of UAV-based dynamic response assessment of bridges. At least one journal paper will be produced from this project and will be submitted for potential publication in a peer-reviewed journal.

### 2.3. ANTICIPATED RESEARCH RESULTS AND DELIVERABLES

- Final Report and ABC-UTC guide on UAV-based dynamic response assessment of bridges
- One comprehensive manuscript that lay the foundation for future-implementation of drones for dynamic and seismic response monitoring of bridges
- Five-minute video summarizing research study and findings

### 2.4. APPLICABILITY OF RESULTS TO PRACTICE

The results from this project are expected to benefit different states DOTs in the future, but an immediate impact is not expected from this fundamental research project.

## 3. TIME REQUIREMENTS (GANTT CHART)

To allow for the completion of all the project tasks, the study will be conducted over a period of 15 months (5 quarters) following the schedule in Table 1.

**Table 1** – Gantt schedule of major project tasks

Task	2021										2022				
	Mar	Ap	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1. Synthesis of available methods	■	■	■	■	■	■	■	■	■	■					
2. V&V drone-based monitoring tests				■	■	■	■	■	■	■					
3. Large-scale drone-based monitoring tests						■	■	■	■	■	■				
4. Final report & dissemination												■	■	■	■

	Completed or work in progress		Remaining
--	-------------------------------	--	-----------

Percentage of completed work: 40%

Percentage of remaining work: 60%

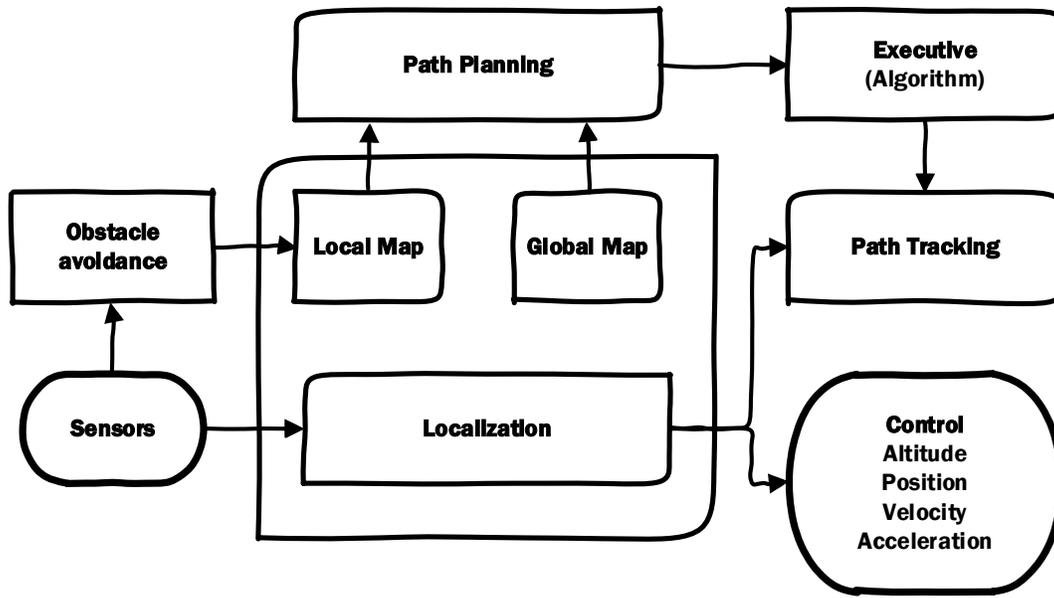
## **Appendix A: Synthesis of Autonomous UAV Navigation And Trajectory Planning For Civil Infrastructures**

Due to the climate change and global warming, disasters – whether it is artificial or natural, are nowadays more frequently disrupting our world even costing human lives. This is more of a concern for the urban areas as the trend of population here is in a rise. In dense urban environments these disasters can cause extensive structural damage to the civil infrastructures not only making recovery efforts slow and painstaking work but also putting responders in harm's way because of the uncertain knowledge of structure's stability. Therefore, post-disaster structural assessment has been placed in the spotlight of the research community (Rastiveis et al., 2013). Now, if the data required to assess the damages could be gathered and processed remotely, early responders and engineers could more effectively respond, perform detailed assessments, and better plan for rescue, recovery and reconstruction of the affected areas (Torok et al., 2013). In this case, significant research attention in civil engineering discipline have been focused on the Aerial robot or more famously known as Unmanned aerial vehicle (UAV) in the past decade due to their cost-effectiveness and convenience for imagery data collection (Meyer, 2015).

Previously UAVs are mostly controlled by Pilots however, with the advent of modern technologies such as AI, accomplish different level of autonomy for UAVs. According to the National Highway Traffic Safety Administration (NHTSA and SEA, 2014) six levels of autonomous vehicle navigation are defined which are also applicable to UAV navigation. Where Level 0 is completely manual control of navigation by pilots. Level 1 is UAV navigation performed by pilots but with some automation applied to specific flight modes, such as holding altitude and hovering. In Level 2 automation, users can define multiple flight modes for automation, and the UAV then navigates based on the scheduled flight modes if there is no unexpected change in the flying environment. In Level 3, a UAV understands changing flying environments and controls flight modes itself to navigate the new environments. In Level 4 navigation, a UAV can adaptively react when there is any system anomaly or a sudden accident, such as a collision with other objects. In Level 5, a UAV can autonomously navigate in all environments and situations.

For post-disaster data collection of civil structures, the navigation space can be considered as a known space with no sudden change of environment, where autonomy of a UAV with scheduled flight plan and some specific flight modes can be accepted to be adequate. Thus, in most cases, as the flying environment is known previously, Level 2 or semi-automated UAV automation is of interest for emergency data collection. (Kang, 2018).

In order to successfully complete a scheduled mission, planning and control of UAV navigation can be accomplished through the steps as shown as Figure 1. With inputs from exteroceptive and proprioceptive sensors (position data sensors), after internal processing of localization and mapping, obstacle avoidance and path planning, the navigation system will finally output continuous control to drive the UAV to the target location.



### UAV Navigation Sensor:

Normally, UAVs obtain states of their own and information of surroundings from both exteroceptive and proprioceptive sensors. Multiple types of sensors are available for a UAV to determine its position. These sensors provide vehicle position data for the UAV to conduct its scheduled mission. The traditional sensors used for navigation are mainly-

1. GPS
2. Axis Accelerometers
3. Gyroscope
4. Vision Camera
  - a. Monocular Camera
  - b. Stereo Camera
  - c. RGB-D Camera Fisheye Camera etc.
5. Laser lighting
6. Ultrasonic Sensors (such as: Ultra-wideband beacon, Ultrasonic beacon sensor)
7. Inertial Navigation System
8. 3D Volumetric Sensors

GPS is the most popular option for position sensors, as GPS sensors are cheaper and easier to use than other types of position sensors. A simple autonomous outdoor navigation by waypoints has been demonstrated using the GPS for localization of the UAV (Carvalho et al., 2017). Unfortunately, GPS cannot be used by a UAV for autonomous flight near some parts of certain structures (e.g., beneath a bridge). The usage of a UAV is often limited to outdoor environments only and complex topographic environments of the navigation space for data collection require higher accuracy in UAV localization than commercial GPS can provide.

Numerous researcher have worked with ultra-wideband beacon system to provide high precision positioning to enable a new range of applications in GPS-denied environments (Vossiek et al., 2003; Zwirello et al., 2012; Sunget al., 2016). However, some experiments have shown millimeter-level accuracy of ultra-wideband beacon positioning systems, but the direct application is not

practical in UAV systems due to high cost and a lack of integration (Zhang et al., 2006). An ultrasonic beacon system (UBS) can be an alternative for a practical mapping and localization system using low-cost hardware. It is cheaper and easier to integrate into and provides centimeter-level accuracy with proper parameter tuning (Díaz et al., 2017). A UBS has multiple mobile and stationary beacons. Where mobile beacons provide 3-dimensional (3-D) position data (x,y,z) of a UAV, and the stationary beacons define the border lines of the map. The stationary beacons are similar to a GPS, sending ultrasonic signals and calculating distances to the mobile beacon installed in the UAV through a router.

Visual sensors are another source to acquire rich information of surroundings based on color, texture, feature, and other visual information. As they are cheaper and easier to deploy, vision-based navigation has becoming a hot spot in the field of UAV research. Different types of cameras are used as visual sensors based on their compactness, weight, cost, flexibility to deployment and visual capacity. However, the performance of visual sensors are dependent on the environment. For example, if the vision sensors cannot obtain features adequate to identify a UAV's location, they incur a high computational cost and accumulate localization errors (Hesset al., 2016).

### **Localization and Mapping:**

Mapping and localization are critical to realization of Level 2 autonomous navigation. To develop autonomous navigation for a UAV, positioning sensors are used for local mapping and a ground station including a mission planner is used to assign a navigation plan. Where a commodity computer can serve as a ground station and the role of mission planner is to assign a navigation plan and monitor the UAV.

Considering the environment and prior information used in navigation, localization, and mapping systems can be roughly classified into following categories:

**I. Random Geometric Graphs:** Random geometric graphs are in general defined as stochastic collections of waypoints in a metric space, connected pairwise by edges if certain conditions (e.g. on the distance between the points) are satisfied. From the theoretical point of view, the study of random geometric graphs makes a connection between random graphs and percolation theory. Much of the literature on random geometric graphs deals with infinite graphs defined on unbounded domains, with vertices generated as a homogeneous Poisson point process. The most studied model of random geo-metric graphs are the following-

1. Infinite Random geometric graph
  - a. Gilbert's disc model
  - b. Boolean model
2. Random finite geometric r-disc graph – models of finite graphs on a bounded domain such Penrose model.
3. Infinite random K-nearest neighbor graph
4. Finite random K-nearest neighbor graph – considers the edges between K-nearest neighbors
5. Online nearest neighbor graph – connected by construction and trivially percolates.

### **II. Visual localization and mapping**

1. Mapless system – Mapless system performs navigation without a known map, and UAVs navigate only by extracting distinct features in the environment that has been observed. Currently, the most commonly used methods in mapless system are-

- a. Optical flow methods – Generally, the optical flow techniques are divided into two categories: global methods and local methods. It is based on the method imitating the bee’s flight behavior by estimating the object movement through cameras on both sides of a UAV. It calculates the optical velocity of two cameras relative to the next waypoint. If they are same, the UAV moves along the central line; otherwise, it moves along the speed of small places forward. It is prone to have a poor performance when navigating in texture-less environment.
  - b. Feature tracking methods – It primarily tracks invariant features of moving elements, including lines, corners, and so on and determines the movement of an object by detecting the features and their relative movement in sequential images. During the process of UAV navigation, invariant features that have been previously observed in the environment are likely to be reobserved from different perspectives, distances, and different illumination conditions. Traditionally, natural features used in localization and mapping are not dense enough to avoid obstacles. Li and Yang (2003) proposed a behavioral navigation method, which utilized a robust visual landmark recognition system combining with a fuzzy-based system for obstacle avoidance.
2. Map based system – Map-based system predefines the spatial layout of environment in a map, which enables the UAV to navigate with detour behavior and movement planning ability. Generally, there are two types of maps:
    - a. Octree maps - Fournier, Ricard, and Laurendeau (2007) used a 3D volumetric sensor to efficiently map and explore urban environments with an autonomous robotic platform. The 3D model of the environment is constructed using a multi-resolution octree. Hornung et al. (2013) developed an open source framework for representation of 3D environment models. The main idea here is to represent the model using octree, not only the occupied space, but also the free and unknown space
    - b. Occupancy Grid Maps - Dryanovski, Morris, and Xiao (2010) used a multi-volume occupancy grid to represent 3D environments, which explicitly stores information about both obstacles and free space.
  3. Map-building systems – Sometimes, due to environmental constraints, it is difficult to navigate with a preexisting accurate map of the environment. Moreover, in some emergent cases when known environment is not a priori, it would be impractical to obtain a map of the target area in advance. Thereby under such circumstances, building maps at the same time as flight would be a more attractive and efficient solution. Map-building system has been widely used in both autonomous and semi-autonomous fields, and is becoming more and more popular with the rapid development of visual simultaneous localization and mapping (visual SLAM) techniques. According to its way of visual sensor image processing, visual SLAM algorithms are divided into three types of methods: indirect method, direct method, and hybrid method.
    - a. Indirect method – Instead of using images directly, the indirect method firstly detects and extracts features from images, and then takes them as inputs for

motion estimation and localization procedures. Current SLAM algorithms are mostly under the feature-based framework. Some of the indirect SLAM based algorithms are-

- i. Monocular Visual SLAM - Davison (2003) presented a top-down Bayesian framework for single camera localization with real-time performance via mapping a sparse set of natural features. It is a milestone for monocular visual SLAM and has a great impact on future work.
- ii. Parallel tracking and mapping algorithm (PTAM) – It is the first one to divide the SLAM system into two parallel independent threads: tracking and map-ping, which was first developed by Klein and Murray (2007). This has almost been the standard of modern feature-based SLAM system.

Some other indirect methods are Sparse indirect method, Dance Indirect method etc.

- b. Direct Method – Though indirect methods prove to perform well in ordinary environment, they are prone to get stuck in texture-less environment. So, direct methods also become a hot spot in the last decade. Different from indirect methods, direct method optimizes geometry parameters using all the intensity information in the image, which can provide robustness to photometric and geometric distortions present in images. Newcombe, Lovegrove, and Davison (2011) presented a real-time monocular SLAM algorithm, DTAM, which estimates the camera's 6DOF motion using direct methods. Engel, Schöps, and Cremers (2014) employed an efficient probabilistic direct approach to estimate semi-dense maps, which can be used for image alignment.
- c. Hybrid Method – Hybrid method combines the direct and indirect methods together. First, it initializes feature correspondences using indirect methods, and then continuously refines camera poses by direct methods, which is faster and more accurate. Forster, Pizzoli, and Scaramuzza (2014) innovatively proposed a semi-direct or hybrid algorithm, SVO, to estimate the state of a UAV. Similar to parallel tracking and mapping algorithm, motion estimation and point cloud mapping are implemented in two threads.

### **Obstacle Detection and Avoidance:**

To detect obstacles and find the distance

1. Optical flow based methods
  - a. Based on change in obstacle size (mechanism of human eye)
  - b. Based on insect's vision optical flow navigation
    - i. Bee's vision – visual nerve structure of insect
    - ii. Based on compound structure of flies
    - iii. Based on distance between objects by the speed of light or light intensity
2. SLAM based methods – precise metric maps, simultaneous localization mapping
  - a. Artificial potential field – for static and dynamic obstacles
  - b. PTAM algorithm
  - c. Oriented fast and rotated brief SLAM