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Review

Survey of computer vision algorithms and applications for unmanned aerial vehicles

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ABSTRACT

This paper presents a complete review of computer vision algorithms and vision-based intelligent applications, that are developed in the field of the Unmanned Aerial Vehicles (UAVs) in the latest decade. During this time, the evolution of relevant technologies for UAVs; such as component miniaturization, the increase of computational capabilities, and the evolution of computer vision techniques have allowed an important advance in the development of UAVs technologies and applications. Particularly, computer vision technologies integrated in UAVs allow to develop cutting-edge technologies to cope with aerial perception difficulties; such as visual navigation algorithms, obstacle detection and avoidance and aerial decision-making. All these expert technologies have developed a wide spectrum of application for UAVs, beyond the classic military and defense purposes. Unmanned Aerial Vehicles and Computer Vision are common topics in expert systems, so thanks to the recent advances in perception technologies, modern intelligent applications are developed to enhance autonomous UAV positioning, or automatic algorithms to avoid aerial collisions, among others. Then, the presented survey is based on artificial perception applications that represent important advances in the latest years in the expert system field related to the Unmanned Aerial Vehicles. In this paper, the most significant advances in this field are presented, able to solve fundamental technical limitations; such as visual odometry, obstacle detection, mapping and localization, et cetera. Besides, they have been analyzed based on their capabilities and potential utility. Moreover, the applications and UAVs are divided and categorized according to different criteria.

1. Introduction

Unmanned Aerial Vehicle (UAV), Remotely Piloted Aerial System (RPAS) or what is commonly known as a drone is the term that describes the aircraft platform without a human pilot onboard. UAV can be either teleoperated remotely by the pilot in the Ground Control Station (GCS) or autonomously using the onboard sensors mounted on it, following preprogrammed operations. However, this terminology not only refers to the vehicle itself, but also to all of the supporting hardware and software including sensors, microcontrollers, ground stations, communication protocols and user interfaces (Beard & McLain, 2012).

There are many classification schemes that have been presented to categorize the UAVs. These schemes are based on a large number of different characteristics; such as the mass, size, mission range, operation altitude, operation duration, Mean Take off Weight (MTOW), flying principle, propulsion mode, operation condition, capabilities or the combination of these characteristics.

Fig. 1 shows the three main classifications and models of UAVs based on its body shape and flying principles.

One of the detailed and widely used schemes has been proposed by van Blyenburgh (2006), as it is shown in Table 1. In which, the UAVs are classified based on the mass, range, altitude, and endurance. Moreover, another scheme based on MTOW and the ground impact risk has been proposed by Dalamagkidis, Valavanis, and Piegl (2012), as it is shown in Table 2.

Although UAVs were designed and supported originally for defense and military purposes; such as aerial attacks or military air cover; to avoid the risk of human lives. Recently, with the developments in microelectronics and the increase of the computing efficiency, small and micro unmanned aerial vehicles (SUAVs and MAVs) have encountered a significant focus among the robotics research community. Furthermore, because of their ability to operate in remote, dangerous and dull situations, especially helicopters and Vertical Take-Off and Landing (VTOL) rotor-craft

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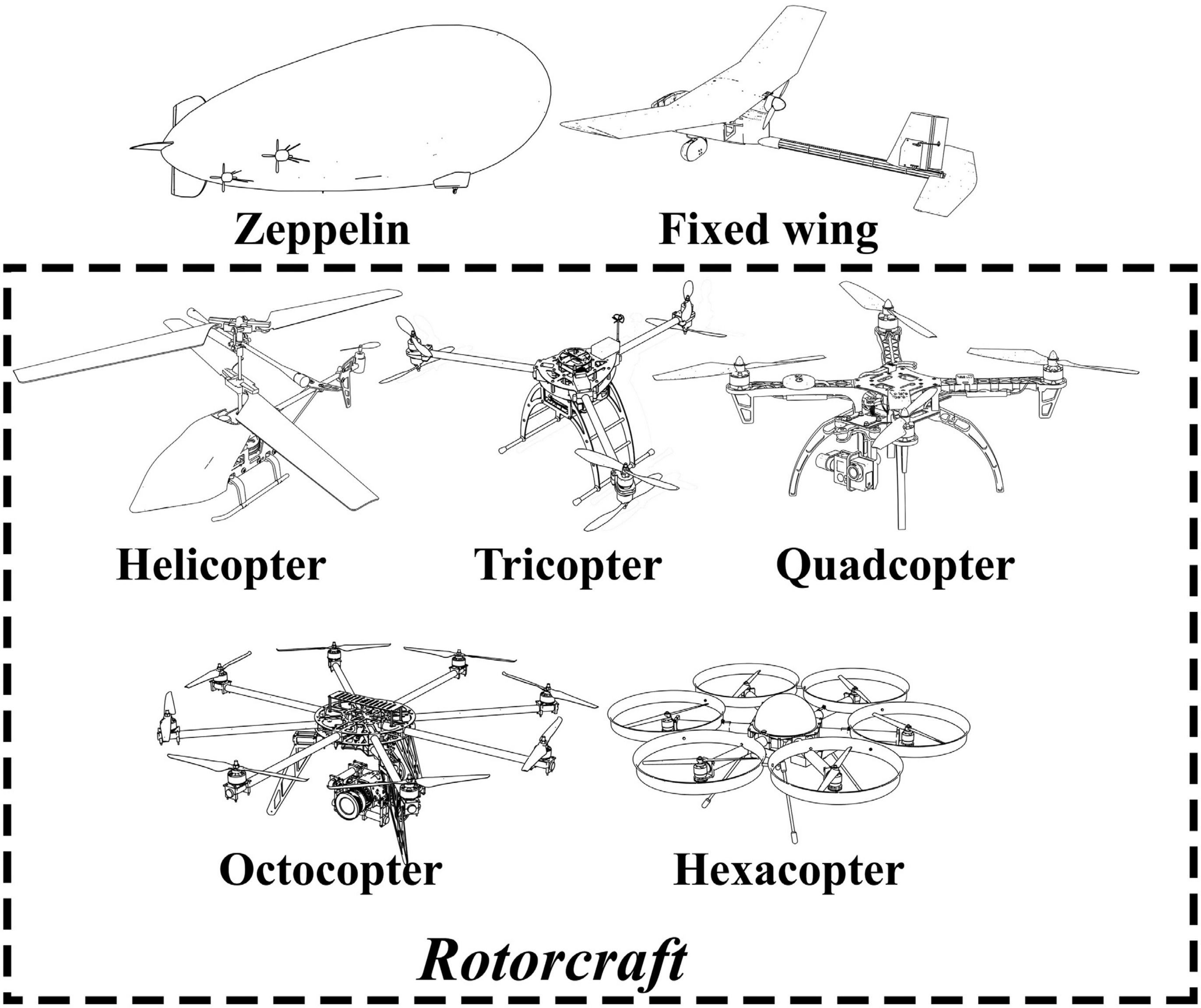

Fig. 1. UAV Models.

Table 1
Classification of UAVs based on mass, range, altitude and endurance (SOURCE van Blyenburgh (2006)).

Category	Mass (kg)	Range (km)	Flight altitude (m)	Endurance (h)
Micro	< 5	< 10	250	1
Mini	< 20/25/30/150[a]	< 10	150/250/300	
Tactical				
Close range (CR)	25–150	10–30	3000	2–4
Short Range (SR)	50–250	30–70	3000	3–6
Medium Range (MR)	150–500	70–200	5000	6–10
MR endurance (MRE)	500–1500	> 500	8000	10–18
Low altitude deep penetration (LADP)	250–2500	> 250	50–9000	0.5-1
Low altitude long endurance (LALE)	15–25	> 500	3000	> 24
Medium altitude long endurance (MALE)	1000–1500	> 500	3000	24–48
Strategic				
High altitude long endurance (HALE)	2500–5000	> 2000	20,000	24–48
Stratospheric (Strato)	> 2500	> 2000	> 20, 000	> 48
Exo-stratospheric (EXO)	TBD	TBD	> 30, 500	TBD
Special task				
Unmanned combat AV (UCAV)	> 1000	1500	12,000	2
Lethal (LET)	TBD	300	4000	3–4
Decoys (DEC)	150–250	0–500	50–5000	< 4

[a] Varies with national legal restrictions.

Category				
Number	$\mathbf{T_{GI}}$[a]	MTOW	Name	Note
0	10^2	Less than 1 kg	Micro	Most countries do not regulate this category since these vehicles pose minimal threat to human life or property
1	10^3	Up to 1 kg	Mini	These two categories roughly correspond to R/C model aircraft
2	10^4	Up to 13.5 kg	Small	
3	10^5	Up to 242 kg	Light/ultralight	Airworthiness certification for this category may be based either on ultralights (FAR [b]part 103), LSA[c] (Order 8130), or even normal aircraft (FAR Part 23)
4	10^6	Up to 4332 kg	Normal	Based on MTOW these vehicles correspond to normal aircraft (FAR Part 23)
5	10^7	Over 4332 kg	Large	These vehicles best correspond to the transport category (FAR Part 25)

[a] T_{GI} is the minimum time between ground impact accidents.
[b] Federal Aviation Regulations.
[c] Light Sport Aircraft.

systems; for example quad/hexa/octo-rotors are increasingly used in several civilian and scientific applications; such as surveying and mapping, rescue operation in disasters (Adams & Friedland, 2011; Erdos, Erdos, & Watkins, 2013), spatial information acquisition, buildings inspection (Choi & Kim, 2015a; Eschmann, Kuo, Kuo, & Boller, 2012), data collection from inaccessible areas, geophysics exploration (Fraundorfer et al., 2012; Kamel, Santana, & De Almeida, 2010), traffic monitoring (Kanistras, Martins, Rutherford, & Valavanis, 2013), animal protection[1] (Xu, Solmaz, Rahmatizadeh, Turgut, & Boloni, 2015), agricultural crops monitoring (Anthony, Elbaum, Lorenz, & Detweiler, 2014), manipulation and transportation[2] (Michael, Fink, & Kumar, 2011) or navigation purposes (Bills, Chen, & Saxena, 2011; Blosch, Weiss, Scaramuzza, & Siegwart, 2010).

With the current technology and the variety and the complexity of the tasks, modern UAVs aim at higher levels of autonomy and performing flight stabilization. The main part of an autonomous UAV is the navigation system and its supporting subsystems. The autonomous navigation system utilizes information from various subsystems in order to achieve three essential tasks: to estimate the pose of the UAV (position and orientation) **(Localization)**, to identify obstacles in the surrounding and act in consequence; in order to avoid them **(Obstacle detection and avoidance)** and send commands to stabilize the attitude and follow guidance objectives **(Control loop)**.

The difficulty appears due to working with SUAVs or MAVs; such as Ar.Drone Parrot[3], DJI Pantom series[4], AscTec Hummingbird[5], Voyager 3[6], 3DR SOLO[7] or TALI H500[8]. That is because of the size of these vehicles is getting smaller (few centimeters) and the weight is getting lighter (few grams), which leads to a significant limitation in the payload capabilities and the power consumption. Therefore, with these properties, mounting onboard sensors that are helpful for the navigation purposes is considered a challenging problem.

In outdoor operations, most of the navigation systems are based on Global Positioning System (GPS) (Hui, Xhiping, Shanjia, & Shisong, 1998; Kim, 2004; Tao & Lei, 2008) to locate their position. In these systems, the precision depends directly on the number of satellites connected. However, GPS-based systems do not provide reliable solutions in GPS-denied environments; such as urban areas, forests, canyons or low altitude flights that can reduce the satellite visibility. Furthermore, in other scenarios like indoor operations, GPS loses totally its efficiency because of the absence of information.

UAVs need a robust positioning system to avoid catastrophic control actions, which can be caused by the errors in the position estimation, so that different approaches are proposed to solve this problem. Using the information provided by the GPS combined with the data obtained by the Inertial Navigation System (INS) is one of the most popular approaches, at which the data of the INS and the GPS are fused together to minimize the position error (Beard et al., 2005; Nakanishi, Kanata, & Sawaragi, 2012; Soloviev, 2010; Yoo & Ahn, 2003). Two main drawbacks appeared of these approaches which affect the localization process. First, the information are still dependent on the external satellite signals and the number of satellites detected. Second, the lack of precision of the IMU measurements because of several generated errors over time.

Therefore, some specific solutions have been provided; such as using radar (Quist, 2015) or laser sensor (Bry, Bachrach, & Roy, 2012; Grzonka, Grisetti, & Burgard, 2012). However, these sensors require more payload capabilities and higher power consumption.

Owing to its capability to provide detailed information about the surrounding environments, visual sensors and computer vision algorithms play a vital role as the main solution in indoor and outdoor scenarios (Blosch et al., 2010; Kamel et al., 2010; Krajnik, Nitsche, Pedre, Preucil, & Mejail, 2012; Mourikis et al., 2009). In addition, visual sensors can be used as stand-alone sensors or combined with other sensors; to improve the accuracy and robustness of the navigation system.

Visual sensors, such as cameras, have the advantage of lightweight, low power consumption and relatively low-cost. In addition, they provide rich information of the environment, which can be processed and applied to real-time applications. However, the accuracy of these approaches depends on different factors; such as images resolution, capturing time, viewing angle, illumination, different structures of aerial images and reference data.

UAV vision-based systems have intelligent capabilities, which are an important brand in Expert Systems, and the applications derived from them have a great potential as a research and innovation field

This Survey presents a literature review of the UAV applications, the algorithms and the techniques that are mainly based on the computer vision applied on the UAVs. In addition, demonstrates the efficiency of the visual devices as a main or complementary sensor that provides information about the environment for the purposes of the UAVs navigation systems.

Moreover, from this literature and by studying several vision-based algorithms, the obtained information and data provided a solid background to proposed different approaches in the field of autonomous UAVs and computer vision. One of these approaches is to present a vision-based system for infrastructure inspection

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[1] http://www.bbc.com/news/business-28132521.
[2] http://www.service-drone.com/en/production/logistics-and-transport.
[3] http://ardrone2.parrot.com/.
[4] http://www.dji.com/products/phantom.
[5] http://www.asctec.de/en/uav-uas-drones-rpas-roav/asctec-hummingbird/.
[6] http://www.walkera.com/en/products/aerialdrones/voyager3/.
[7] https://3dr.com/solo-drone/.
[8] http://www.walkera.com/en/products/aerialdrones/talih500/.

using a UAV (Al-Kaff et al., 2017b). In addition, another approach was presented to mimic the human behavior in detecting and avoiding frontal obstacles using monocular camera (Al-Kaff, García, Martín, De La Escalera, & Armingol, 2017a).

The remainder of this paper is organized as follows; Section 2 introduces a review of the computer vision algorithms and techniques that are used with the UAVs. Section 3 presents the navigation systems and its subsystems (Pose estimation, Obstacle detection and avoidance, and Visual servoing), followed by showing different autonomous application based on computer vision in Section 4. Finally, in Section 5 conclusion is summarized.

2. Computer vision for UAVs

Computer vision plays a vital role in the most of the Unmanned Aerial Vehicles (UAVs) applications. These applications vary from a simple aerial photography, to very complex tasks such as rescue operations or aerial refueling. All of them require high level of accuracy in order to provide reliable decision and maneuver tasks.

Aerial imagery or aerial filming is considered one of the basic and demanding application; such as filming sports games[9], events[10] or even weddings[11].

With the advances in computer vision algorithms and sensors, the concept of using aerial images just for photography and filming was changed to be used widely in more complex applications; such as thematic and topographic mapping of the terrain (Ahmad et al., 2013; Cui, Lin, & Zhang, 2007; Li & Yang, 2012; Ma, Li, Tong, Wang, & Cheng, 2013; Tampubolon & Reinhardt, 2014); exploration of un reachable areas such as islands (Ying-cheng et al., 2011), rivers (Rathinam et al., 2007), forests (Cui et al., 2014; Yuan, Liu, & Zhang, 2015a) or oceans (Sujit, Sousa, & Pereira, 2009a; 2009b); surveillance purposes (Geng et al., 2014; Govindaraju, Leng, & Qian, 2014; Lilien et al., 2015; Semsch, Jakob, Pavlicek, & Pechoucek, 2009); and search and rescue operations after catastrophes (Erdos et al., 2013; Kruijff et al., 2012; Waharte & Trigoni, 2010).

Another widely demanded application that takes the advantages of the aerial imagery over the traditional sensing, is the traffic monitoring (Kanistras et al., 2013). Traffic monitoring using UAVs includes the estimation of the traffic flow behavior (Heintz, Rudol, & Doherty, 2007; Kim et al., 2012), traffic speed (Ke, Kim, Li, & Wang, 2015), roads state (Lin & Saripalli, 2012; Zhou, Kong, Wei, Creighton, & Nahavandi, 2015), in addition to the emergencies and car accidents (Puri, 2005).

Furthermore, wide variety of different autonomous applications have been presented; such as autonomous take-off and landing (Cabecinhas, Naldi, Marconi, Silvestre, & Cunha, 2010; Jung, Bang, & Lee, 2015; Lee, Su, Yeah, Huang, & Chen, 2014b; Sanchez-Lopez, Saripalli, Campoy, Pestana, & Fu, 2013), autonomous aerial refueling (Aarti & Jimoh O, 2013; Campa, Napolitano, & Farvolini, 2009; Xufeng, Xinmin, & Xingwei, 2013; Yin et al., 2016), autonomous tracking (Achtelik, Zhang, Kuhnlenz, & Buss, 2009; Lin, Lum, Chen, & Lee, 2009; Martínez Luna, 2013; Zhao, Fei, & Geng, 2013) or autonomous route planning (Govindaraju et al., 2014; Kothari, Postlethwaite, & Gu, 2009; Sangyam, Laohapiengsak, Chongcharoen, & Nilkhamhang, 2010; Yamasaki, Sakaida, Enomoto, Takano, & Baba, 2007; Yang, Qi, Xiao, & Yong, 2014), where high levels of accuracy of localization, detection and tracking are required.

Different surveys that cover different computer vision concepts, techniques and applications that are related to UAVs are presented in Campoy et al. (2009) (visual servoing), Liu and Dai (2010) (aerial surveillance and multi-UAV cooperation), Adams and Friedland (2011) (disaster research), Kanistras et al. (2013) (traffic monitoring), and Yuan, Zhang, and Liu (2015b) (forest fire monitoring).

This survey discusses the evaluation of vision-based algorithms, methods and techniques that are related to the UAVs navigation systems in the last decade. In addition, it presents the most modern and demanded applications that are based on computer vision.

3. UAVs' navigation systems

Modern UAVs aim at higher levels of autonomy with accurate flight stabilization. The main part of an autonomous UAV is the navigation system and its supporting subsystems. The navigation system utilizes information from various sensors, in order to estimate the pose of the UAV in terms of positions (x, y, z) and orientations (ϕ, θ, ψ). Other supporting systems solve relevant tasks such as obstacles detection and tracking (static or dynamic), or obstacle avoidance.

With this increase in the levels of autonomy and flight stabilization, robust and efficient navigation systems are required. Computer vision algorithms by means of monocular cameras can be helpful to enhance the navigation activities. As it is shown in Table 3, the navigation systems are divided into three main subsystems: **Pose estimation** which aims to estimate the position and the attitude of the UAV in two and three dimensional representations, **Obstacle detection and avoidance** that detects and feeds back the position of the obstacles that are situated in the path of the UAV, and finally the **Visual servoing** subsystem at which the maneuver commands are managed and sent in order to maintain the flight stability and following the path. The following Sections (3.1, 3.2 and 3.3) address these three navigation subsystems.

3.1. Pose estimation

Pose estimation is the process of estimating the position and the orientation of the vehicle during the motion; based on the information generated by one or more sensors; such as IMU, GPS, vision, laser, ultrasonic, etc. The information can be generated by each sensor separately or by fusing the data from different sensors. Pose estimation is considered as a fundamental phase for any navigation or mapping processes.

3.1.1. Global positioning system (GPS)

Global Positioning System (GPS) (Kaplan & Hegarty, 2006; Zogg, 2009) or the Satellite-based Navigation System (SNS) is considered as one of the most known approaches that is used with UGVs (Abbott & Powell, 1999; Amini, Vaghefi, de la Garza, & Buehrer, 2014; Wei, Cappelle, & Ruichek, 2011; YAĞIMLI & Varol, 2009; Yoon, Park, & Kim, 2006), UAVs (Cho et al., 2007; Hui et al., 1998; Isaacs et al., 2014; Kim, 2004; Yun, Peng, & Chen, 2007) or even Autonomous Underwater Vehicle (AUV) (Lee, Li, Hoang, & Lee, 2014a; Meldrum & Haddrell, 1994; Taraldsen, Reinen, & Berg, 2011) to provide the 3D position for navigation purposes.

In most cases, the GPS is used as the main sensor for localization process to obtain the position of the vehicles. One of the earlier works that is based on the GPS for localization with UAVs was presented by Hui et al. (1998). In this work, the authors showed the effect of using the Differential Global Positioning System (DGPS); to reduce the errors (satellite clock error, satellite position error and delay error) comparing to the use of the GPS receiver alone. Similarly in Cho et al. (2007), a DGPS is implemented to a single antenna receiver; in order to increase the accuracy of the positioning information.

In these systems, the precision depends directly on the number of satellites connected. This number can be insufficient on urban environments due to buildings, forests or mountains that can reduce the satellite visibility. Furthermore, in other scenarios; such

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[9] The Future of Sports Photography: Drones.

[10] Airborne camera makes concert scene.

[11] Camera in the Sky: Using Drones in Wedding Photography and Videos.

System	Description	Method	Related work
Localization	Estimate the UAV 2D/3D Position and Orientation	VO	(Fu et al., 2015; Nikolic et al., 2014; Omari et al., 2015; Warren & Upcroft, 2013), (Grabe et al., 2012; Krajnik et al., 2012; Lim et al., 2012; Mouats et al., 2015),(Domínguez, Zalama, García-Bermejo, Worst, & Behnke, 2013; Romero et al., 2013; Zhang, Stahle, Gaschler, Buckl, & Knoll, 2012; Zhang et al., 2014),(Bloesch, Omari, Hutter, & Siegwart, 2015; Chunhui, Rongzhi, Tianwu, & Quan, 2014; Willis & Brink, 2016)
		SLAM	(Ahrens et al., 2009; Bonin-Font et al., 2015; Mart et al., 2015), (Blosch et al., 2010; Kerl et al., 2013; Zeng et al., 2014; Zhang et al., 2015), (Engel et al., 2014; Fu, Olivares-Mendez, Suarez-Fernandez, & Campoy, 2014; Meng, de Silva, & Zhang, 2014; Weiss, Scaramuzza, & Siegwart, 2011),(Davison et al., 2007; Li, Aouf, & Nemra, 2012b; Milford et al., 2011)
Obstacle Detection and Avoidance	Detecting the possible obstacles and collision zones and making the suitable avoidance decisions	Stereo	(Gao et al., 2011; Hrabar, 2008; Jian & Xiao-min, 2011; Na et al., 2011) (Broggi et al., 2013; Gageik, Benz, & Montenegro, 2015; Hou et al., 2016; Odelga, Stegagno, & Bülthoff, 2016) (Majumder et al., 2015)
		Monocular	(Al-Kaff, Meng, Martín, de la Escalera, & Armingol, 2016; Bills et al., 2011; Ma et al., 2015; Saha et al., 2014) (Lenz, Gemici, & Saxena, 2012; Mori & Scherer, 2013)
Visual Servoing	Maintain UAV stability and flying maneuvers based on visual data		(Lee et al., 2012; Lyu et al., 2015; Neff, Lee, Chitrakaran, Dawson, & Burg, 2007; Olivares-Mendez et al., 2015) (Bošnak, Matko, & Blažič, 2012; Kurnaz, Cetin, & Kaynak, 2010; Shang, Liu, Zhao, & Chen, 2016; Zhang, Fang, Liang, & Zhang, 2016)

as indoor flying, GPS loses its efficiency because of the absence of the satellite signals. Therefore, some expensive external localization systems are used; such as the VICON systems (Al Habsi, Shehada, Abdoon, Mashood, & Noura, 2015; Bry et al., 2012; Mellinger, Michael, & Kumar, 2012; Michael et al., 2011) to capture the motion of the UAV in indoor environments.

3.1.2. GPS-aided systems

Although stand-alone GPS is useful to estimate the position of the vehicles, it also generates errors because of the disability to receive satellites signals, or by the jamming of the signals that consequently may lead to lose navigation information.

UAVs need a robust positioning system to avoid catastrophic control actions that can be caused by errors in position estimation, so that different approaches are used to solve this problem. One example of these approaches is GPS-aided systems. In these approaches the gathered data from the GPS are fused with the information obtained from other sensors, this multi-sensory fusion can be of two sensors (Beard et al., 2005; Qingbo, Nan, & Baokui, 2012; Tao & Lei, 2008) or more than two sensors (Jiong, Lei, Jiangping, Rong, & Jianyu, 2010; Nakanishi et al., 2012; Vincenzo Angelino, Baraniello, & Cicala, 2013; Ziyang, Qiushi, Chen, & Ju, 2014).

GPS/INS is one of the most popular configuration, at which the data from the INS and the GPS are fused together; to compensate the generated errors from both sensors and increase the precision of the localization process. In Yoo and Ahn (2003), the data from multiple antennas GPS are fused with the information from the onboard INS using linear Kalman filter. However, this algorithm has been implemented to be used with UAVs, although the experiments have been performed on a ground vehicle.

Similar works were presented to reduce the position error using Extended Kalman Filter (EKF) (Barczyk & Lynch, 2012), or by employing the Kalman-Complementary filtering (Yun et al., 2007), or by fusion Strap-down Inertial Navigation System (SINS) data wish the GPS (Qingbo et al., 2012; Tao & Lei, 2008).

In Vincenzo Angelino et al. (2013), an Unscented Kalman Filter (UKF) was implemented to fuse the GPS data with the camera information and the data obtained from the IMU in order to improve the localization process. This fusion showed improvement in the results comparing to the result of each sensor, However, the experiments were limited to simulations.

Moreover, in other works (Jiong et al., 2010; Nakanishi et al., 2012), an altitude sensor was added to the GPS/INS system; in order to improve the reliability and increase the accuracy of the navigation by enhancing the accuracy of the GPS vertical measurements. But these systems still have inaccurate results, especially if the UAV flies in low altitudes; because the barometer is affected by the ground effect and estimated altitudes lower than the actual ones (Nakanishi, Kanata, & Sawaragi, 2011).

Another multi-sensor fusion based system for multiple MAVs was introduced in Wang and Ge (2011). At which, the data of the GPS are fused with the information from the Identification Friend-or-Foe (IFF) radar system for localization enchantment using EKF. In the simulations, it has been proved that by using two GPS receivers better information is obtained rather than a single GPS receiver.

In Isaacs et al. (2014), a GPS localization system is used on Lockheed Martin's Samari MAV. At which, a greedy source seeking algorithm was used to track the radio frequency sources by estimating the angle of arrival to the source while observing the GPS signal to noise ratio; in order to keep the quality of the GPS signal.

Two main drawbacks appeared on these approaches, affecting the localization process. First, the information are still dependent on the external satellite signals. Second, the lack of precision of the IMU measurements. These difficulties favored the apparition of vision-based systems. These novel approaches enhance the localization by means of computer vision-based algorithms.

3.1.3. Vision-based systems

Owing to the limitations and drawbacks of the previous systems, vision-based pose estimation approaches have become one of the main topics in the field of intelligent vehicles applications and gain more popularity to be developed for UGVs (Scaramuzza, Fraundorfer, & Siegwart, 2009; Tardif, Pavlidis, & Daniilidis, 2008; Zhang, Singh, & Kantor, 2014), AUV (Bonin-Font, Cosic, Negre, Solbach, & Oliver, 2015; Dunbabin, Corke, & Buskey, 2004; Kunz & Singh, 2010; Mehmood, Choudhry, Anwar, Mahmood, & Khan, 2016), and UAVs (Caballero, Merino, Ferruz, & Ollero, 2009; Fraundorfer et al., 2012; Kneip, Chli, & Siegwart, 2011; Lindsten et al., 2010; Yol et al., 2014).

Regardless to the type of the vehicle and the purpose of the task, different approaches and methods have been proposed. These methods differ on the type of the visual information used; such as horizons detection (Dusha, Boles, & Walker, 2007; Grelsson, Linköpings universitet, & Institutionen för systemteknik, 2014), landmarks tracking (Amor-Martinez, Ruiz, Moreno-Noguer, & Sanfeliu, 2014; Eberli, Scaramuzza, Weiss, & Siegwart, 2011), or edges detection (Kim, 2006; Wang, 2011). Furthermore, they can be differentiated based on the structure of the vision system: it can be monocular (Milford, Schill, Corke, Mahony, & Wyeth, 2011; Yang, Scherer, & Zell, 2013; Zeng, Wang, Liu, Chen, & Deng, 2014), binocular (Vetrella, Savvaris, Fasano, & Accardo, 2015; Warren, 2015), trinocular (Jeong, Mulligan, & Correll, 2013; Martínez, Campoy, Mondragón, & Olivares Mendez, 2009), or omnidirectional (Amorós, Paya, Valiente, Gil, & Reinoso, 2014; Killpack, Deyle, Anderson, & Kemp, 2010; Scaramuzza & Siegwart, 2008; Wang, Zhao, Davoine, & Zha, 2012b) camera system.

Some of the early experimental works that use visual information; in order to estimate the aircraft attitude were presented in Todorovic, Nechyba, and Ifju (2003), Cornall and Egan (2004), Cornall, Egan, and Price (2006), Thurrowgood, Soccol, Moore, Bland, and Srinivasan (2009). These approaches are based on the skyline segmentation using forward-looking camera. In these approaches, Bayesian segmentation model with a Hidden Markov Trees (HMT) model were used to identify the horizon based on the color intensities, and texture clues; in order to estimate the roll angle or both roll and pitch angles, as the work presented in Dusha et al. (2007). These approaches provide successful results in high altitudes where the process of skyline segmentation is relatively easy. On the other hand, in low altitudes or indoor environments, the possibility to detect the horizon is very low due to the complexity of this kind of environments.

Two famous philosophies have appeared to deal with the vision-based pose estimation problem; Visual Simultaneous Localization And Mapping (VSLAM) and Visual Odometry (VO).

SLAM. Simultaneous Localization And Mapping (SLAM) algorithms (Bailey & Durrant-Whyte, 2006; Csorba, 1997; Durrant-Whyte & Bailey, 2006), in general aim to construct a consistent map of the environment and simultaneously estimate the global position of the robot within this map.

Approaches such as those that have been presented in Angeli, Filliat, Doncieux, and Meyer (2006), Ahrens, Levine, Andrews, and How (2009), Blosch et al. (2010), introduced different camera based algorithms; such as Parallel Tracking and Mapping (PTAM) (Klein & Murray, 2007) and MonoSLAM (Davison, Reid, Molton, & Stasse, 2007) to perform VSLAM on aerial vehicles.

Blosch *et al.* used a downward looking camera on the Hummingbird quadcopter for a vision-based approach for localization (Blosch et al., 2010). The pose was estimated using the VSLAM algorithm, and then a Linear Quadratic Gaussian (LQG) control design with Loop Transfer Recovery (LTR) (LQG/LTR) applied; to stabilize the vehicle at a desired setpoints.

In Milford et al. (2011), a vision-based SLAM with visual expectation algorithm was introduced. In this approach, a place recognition algorithm based on the patch tracking is used; to estimate the yaw angle and the translation speed of the vehicle. In addition, the visual expectation algorithm is used to improve the recall process of the visited places. This is achieved by comparing the current scene with the library of saved templates. Finally, both algorithms are combined to a RatSLAM (Milford, Wyeth, & Rasser, 2004) for constructing the maps. However, this system loses its efficiency with the new scenes that are not visited before by the vehicle.

In Kerl, Sturm, and Cremers (2013), a SLAM approach with RGB-D cameras has been presented. In this approach, direct frame-to-frame registration method, with the entropy-based model, was used to reduce the drift error of the global trajectory.

Another direct frame registration method has been presented in Engel, Schöps, and Cremers (2014). In contrast to the RGB-D approach, this method implemented a monocular SLAM with the advance of the ability to construct large scale maps (Fig. 2).

A laser-assisted system was presented in Zeng et al. (2014) to estimate the attitude of the UAV. At which, the pose of the UAV is obtained by a laser scan matching based on the Sum of Gaussian (SoG). A laser spot is captured by a camera mounted on the UAV, and by using gray correlation template matching model, the distance of the spot is obtained. Then, the pose of UAV is estimated by using SoG. In addition, EKF is used to combine the inertial information to the visual system; in order to improve the navigation process.

Another VSLAM approach was presented in Zhang, Xian, Zhao, and Zhang (2015) to control a nano quadcopter. The motion of the quadcopter has been obtained based on an optical flow model. In addition, to eliminate the drift error in the flight, a PTAM was used. Similarly, to the previous work, a Kalman filter was used to fuse the data from the IMU and the barometer, with the visual information; in order to improve the motion estimation. The main drawback of this system is the difficulty to achieve the hover mode for a long time, this is because of the limitation of the optical flow algorithm.

Although SLAM, or in particular VSLAM, is considered to be a precise method for pose estimation purposes, the outliers in the detection affect the consistently of the constructed map. Furthermore, these algorithms are complex and computationally expensive.

Visual odometry. Visual Odometry (VO) algorithms (Nister, Naroditsky, & Bergen, 2004; Scaramuzza & Fraundorfer, 2011) handle the problem of estimating the 3D position and orientation of the vehicle. The estimation process performs sequential analysis (frame after frame) of the captured scene; to recover the pose of the vehicle. Similar to VSLAM this visual information can be gathered using monocular cameras (Guizilini & Ramos, 2011; Roger-Verdeguer, Mannberg, & Savvaris, 2012; Romero, Salazar, Santos, & Lozano, 2013; Wang, Wang, Liang, Chen, & Wu, 2012a) or multiple cameras systems (Maimone, Cheng, & Matthies, 2007; Mouats, Aouf, Chermak, & Richardson, 2015; Warren & Upcroft, 2013).

In contrast to VSLAM, VO algorithms deal to estimate consistent local trajectories, in each instant of time without maintaining all the previous poses.

VO firstly proposed by NistÃ©r (Nister et al., 2004; Nistér, Naroditsky, & Bergen, 2006), it was inspired by the traditional wheel odometry, to estimate the motion of ground vehicles using stereo camera, incrementally by detecting the Harris corners (Harris & Stephens, 1988) in each frame. In this approach, the image features were matched between two frames, and linked into image trajectories, by implementing a full structure-from-motion algorithm that takes advantage of the 5-point algorithm and RANdom SAmple Consensus (RANSAC) (Fischler & Bolles, 1981). From his experiments, it was proved that the VO accuracy was better than the wheel odometry with position error of [0.1–3%] of the total trajectory.

Within the NASA Mars Exploration Program (MER) (Cheng, Maimone, & Matthies, 2005; Maimone et al., 2007) a stereo VO algorithm based also on Harris corner detector has been implemented on the MER rover; to estimate its 3D pose in the terrain Mars (feature-poor terrain). Related works to employ VO algorithms on the ground vehicles have been presented in Scaramuzza et al. (2009), Lin, Jiang, Pu, and Song (2010), Fabian and Clayton (2014) and Soltani, Taghirad, and Ravari (2012).

A hybrid model of visual-wheel odometry is presented in Zhang et al. (2014). In this model, the position of the ground vehicle is estimated based mainly on monocular camera, then both of the rotation and translation are recovered separately using the Ackermann steering model.

Recently different motion estimation schemes based on stereo VO algorithms are presented; to be applied on the UAVs such as the works in Warren and Upcroft (2013), Omari, Bloesch, Gohl, and Siegwart (2015), Fu, Carrio, and Campoy (2015).

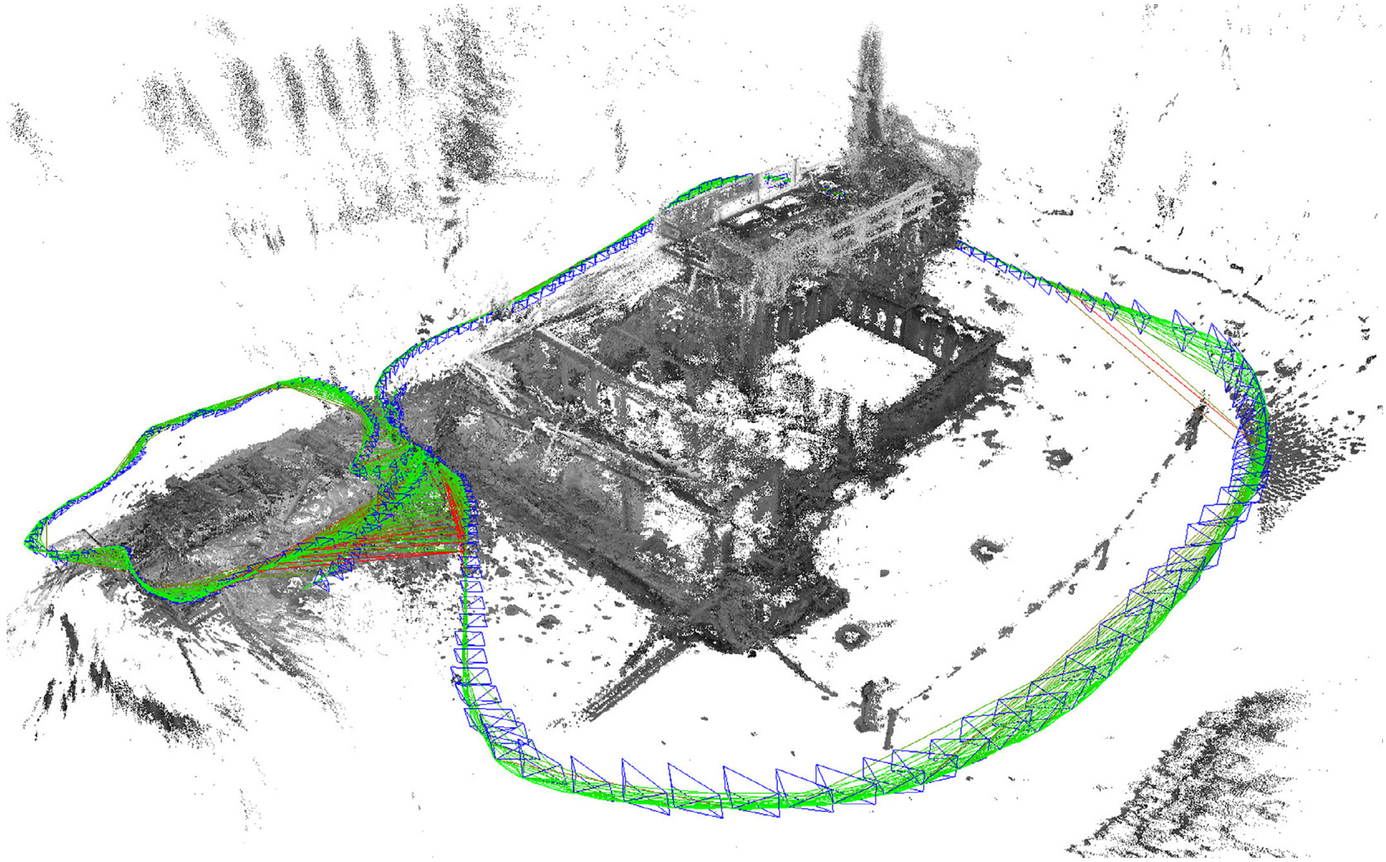

Fig. 2. Example of LSD-SLAM (Engel et al., 2014).

In Warren and Upcroft (2013), stereo VO system is presented to enhance the initial pose of the stereo camera. This information is based on a sequence of 8–10 frames, instead of using a single pair. Although this system showed good results in large-scale environments, it cannot be used with the MAVs because of the requirement of a big size stereo camera with a baseline of 78 cm.

On the other hand, in Omari et al. (2015), Fu et al. (2015), a new small size RGB-D VI-sensor (Nikolic et al., 2014) has been used on the MAVs. The first work used a probabilistic model to incorporate the RGB-D camera with the IMU, to estimate the motion of the UAV, and build 3D models of the environment. The later work, presented a stereo VO algorithm based on feature tracking technique, where a combination of Features from Accelerated Segment Test (FAST) (Rosten & Drummond, 2006) and Binary Robust Independent Elementary Features (BRIEF) (Calonder, Lepetit, Strecha, & Fua, 2010) are used for the feature tracking step. However, this combination provides fast processing, but it cannot provide accurate data compared to other algorithms such as Scale-Invariant Feature Transform (SIFT) (Lowe, 2004).

Furthermore, although the stereo camera used in these systems is small and light weight, suitable to mount on a small UAVs, the small baseline caused a significant limitation of the system in the large-scale environments.

Research in Grabe, Bulthoff, and Robuffo Giordano (2012) introduced an optical flow vision-based system, combined with the onboard IMU to estimate the motion of the UAV. In this system, the Shi-Tomas (Shi & Tomasi, 1994) algorithm is used for the feature detection, then the pyramidal Lucas–Kanade (LK) model (Varghese, 2001) is used to track the detected feature. Then the obtained velocity from IMU is used to compensate the velocity error estimated by the optical flow algorithm. The same concept of using the combination of the optical flow and IMU model is presented in Lim, Lee, and Kim (2012); for controlling the hover flight mode of the quadcopter. The main limitation of the model, is providing an unbalanced representation of the scene, when there are insufficient number or features, or if the tracked features are not distributed across the image plane.

A position estimation approach of aerial vehicles, based on line detection and corner extraction is presented in Kamel et al. (2010). In which, lines and corners are extracted by Hough transform and Harris corners detection, then the rotation, translation and scale are estimated. Finally, a geometric model estimation is used to map the high resolution image onto a low resolution, which provides position estimation.

A monocular camera-based navigation system for an autonomous quadcopter was presented in Krajnik et al. (2012); to determine only the UAV yaw and vertical speed. One of the limitation of this method is that the UAV can only operate along paths it has traveled during a human-guided training run. Moreover, these paths can be composed only from straight-line segments with a limited length.

In Samadzadegan, Hahn, and Saeedi (2007), they presented an approach of vision-based (2D–3D) pose estimation of UAVs. In which, the algorithm aligns 2D data from aerial image into a geo-referenced ortho satellite image 3D based on fuzzy reasoning system.

An euclidean homography method was presented in Kaiser, Gans, and Dixon (2006); to maintain the vehicle navigation, when GPS signals are not available. This system allows sets of feature points of a series of daisy-chained images to be related; such that the position and orientation can continuously be estimated. This method was limited to simulation results, and it has the disability to estimate the depth where there is a change in environment planes.

Similarly in Madison, Andrews, Paul DeBitetto, Rasmussen, and M. Bottkol (2007), a vision-aided navigation system is used to replace GPS when it is temporarily denied. A single camera system detects, tracks, and geo-locates 3D landmarks observed in the images; to estimate absolute position and velocity data.

Another multi-sensor data fusion model is introduced in Samadzadegan and Abdi (2012). In which, the system uses an EKF to fuse the vision information which provides attitude and position observations, with the data from the IMU motion model, for accurately determining the pose parameters of the vehicle.

3.2. *Visual obstacle detection and avoidance*

Obstacle detection and avoidance is a fundamental phase in any autonomous navigation system. In addition, this process is considered as a challenging process, especially for vision-based systems.

In vision-based navigation systems, different approaches were presented to solve the problem of obstacle detection and avoidance. Approaches such as Beyeler, Zufferey, and Floreano (2007), Hrabar (2008), Gao, Ai, Rarity, and Dahnoun (2011), Na, Han, and Jeong (2011), built a 3D model of the obstacle in the environment. Other works calculate the depth (distance) of the obstacles; such as in Jian and Xiao-min (2011) and Saha, Natraj, and Waharte (2014). All these approaches have the disadvantage that they are computationally expensive.

A technique based on stereo cameras; in order to estimate the proximity of the obstacles, was introduced in Majumder, Shankar, and Prasad (2015). Based on the disparity images and the view angle, the system detects the size and the position of the obstacles, and calculates the relation of the size and its distance to the UAV.

Another stereo vision-based obstacle detection for ground vehicles is presented in Broggi, Cattani, Patander, Sabbatelli, and Zani (2013). In which, a Voxel map is reconstructed from the 3D point cloud provided by the stereo camera. Thereafter, a linear Kalman filter is used to distinguish between the moving and stationery obstacles. Finally, with the aid of the computed egomotion, the system estimates the position and the velocity of the detected obstacles.

On the other hand, bio-inspired (insect, animal or human like) approaches estimate the presence of the obstacle efficiently, without calculating the 3D model, e.g. using motion parallax (i.e. optical flow) (Beyeler et al., 2007; Hrabar, Sukhatme, Corke, Usher, & Roberts, 2005; Merrell, Lee, & Beard, 2004) or perspective cues (Bills et al., 2011; Celik, Chung, Clausman, & Somani, 2009; Chavez & Gustafson, 2009).

In de Croon, de Weerdt, De Wagter, and Remes (2010), it was presented an approach based on the texture and color variation cue; to detect obstacles for indoor environments. However, this approach only works with detailed textures.

Working with Hybrid MAVs, Green *et al.* proposed an optical flow based approach for lateral collision avoidance, mimicking the biological flying insects (Green & Oh, 2008).

In Lee, Lee, Park, Im, and Park (2011), the SIFT descriptor and Multi-scale Oriented-Patches (MOPS) are combined to show the 3D information of the obstacles. At which, the edges and corners of the object are extracted using MOPS by obtaining and matching the MOPS feature points of the corners, then the 3D spatial information of the MOPS points is extracted. After that, SIFT is used to detect the internal outline information.

In Bills et al. (2011), it was proposed an approach for indoor environments, with a uniform structure characteristics. In this work, Hough Transform is used to detect the edges that are used; to classify the essence of the scene based on a trained classifier. However, their experiments were limited to corridors and stairs areas.

A saliency method based on Discrete Cosine Transform (DCT) is presented in Ma, Hu, Shen, Kong, and Zhao (2015) for obstacle detection purposes. From the input images, the system assumed that the obstacle is a unique content in a repeated redundant background, then by applying amplitude spectrum suppression, the method can remove the background. Finally, by using the Inverse Discrete Cosine Transform (IDCT) and a threshold algorithm, the center of the obstacle is obtained. Furthermore, a pinhole camera model is used to estimate the relative angle between the UAV and the obstacle, this angle is used with a PD controller to control the heading of the UAV for obstacle avoidance.

In Saha et al. (2014), the authors presented an approach for measuring the relative distance to the obstacle. At which, the camera position is estimated based on the EKF and the IMU data. Then the 3D position of the obstacle can be calculated by back projecting the detected features of the obstacle from its images.

An expansion segmentation method was presented in Byrne and Taylor (2009). At which a conditional Markov Random Field (MRF) is used to distinguish if the frontal object may represent a collision or not. Additionally, an inertial system is used to estimate the collision time. However, the experiments of this work was limited to simulations.

Another approach presented in Mori and Scherer (2013), used feature detection in conjunction with template matching; to detect the size expansions of the obstacles . However, the experiments were limited on a tree-like obstacles and did not show results of other shapes.

In Eresen, İmamoğlu, and Önder Efe (2012), an optical flow based system has been presented to detect the obstacles and junctions in outdoor environments. This system is based on the *Horn & Schunk* method (Horn & Schunck, 1992); in order to look for the collision free areas and the junctions in a predefined flight path. In addition, a PID controller is used as a low-level control scheme. However, all the experiments were limited to virtual flights in Google Earth software.

Kim *et al.* presented a block-based motion estimation approach for moving obstacles (humans) (Kim & Do, 2012). In which, the input image is divided in smaller blocks and comparing the motion in each block through consecutive images. This approach works well with large size obstacles (humans).

In addition, surveys of different approaches of UAVs guidance, navigation and collision avoidance methods are presented in Albaker and Rahim (2009) and Kendoul (2012).

3.3. *Visual servoing*

Visual Servoing (VS) is the process of using the information that are obtained by the visual sensors as a feedback in the vehicle (UAV) control system. Different inner-loop control systems have been employed to achieve the stabilization of the UAVs, such as PID (Golightly & Jones, 2005; Kada & Gazzawi, 2011; Martin, 2012), optimal control (Suzuki, Ishii, Okada, Iizuka, & Kawamur, 2013), sliding mode (Lee, Ryan, & Kim, 2012), fuzzy logic (Limnaios & Tsourveloudis, 2012), and cascade control structure (Bergerman, Amidi, Miller, Vallidis, & Dudek, 2007). References; such as Wagtendonk (2006), Beard and McLain (2012), Elkaim, Lie, and Gebre-Egziabher (2015) provide detailed information about the principles and theories related to the UAV flight controlling. On the other hand, higher level control systems can be used for guidance purposes; such as waypoints rang or path following (Elkaim et al., 2015; Olivares-Méndez, Mondragón, Campoy, & Martínez, 2010).

A comparative study has been introduced in Altug, Ostrowski, and Mahony (2002) to evaluate two controllers (*mode-based feedback linearizing* and *backstepping-like* control) using visual feedback. At which, an external camera and the onboard gyroscopes are used to estimate the UAV angles and position. From the simulations, it has been found that the backstopping controller is better than feedback stabilization.

In Lee et al. (2012), an image-based visual servoing has been described; to use the 2D information as an input to the adaptive sliding mode controller for autonomous landing on a moving platform.

A visual system based on two cameras (external camera located on the ground and onboard camera), was presented in is Minh and Ha (2010) for flight stabilization purposes in the hover modes. At which, both cameras were set to see each other, and a tracking algorithm was used to track color blobs that are attached to the cameras. Thereafter, the pose of the UAV was estimated. Finally, the Linear Quadratic Tracking (LQT) controller and optimal LQG control were used with the visual feedback in order to stabilize the attitude of a quadcopter. However, the performance of the proposed controller was verified in simulations.

A design of fuzzy control for tracking and landing on a helipad has been presented in Olivares-Mendez, Kannan, and Voos (2015). In this approach, four fuzzy controllers were implemented to control the longitudinal, lateral, vertical, and heading velocities to keep the UAV in the center of the moving helipad. The estimation of the UAV pose is based on a vision algorithm.

An inertial-visual aided control system was presented in Baik, Shin, Ji, Shon, and Park (2011). Kanade–Lucas–Thomasi (KLT) feature tracker algorithm is used to estimate the UAV attitude, then the values are sent to a PID control system. However, this control system is lacking of a filtering stage, resulting a significant drift error.

Recently, Lyu *et al.* proposed a visual servoing system that is based on cooperative mapping control framework of multiple UAVs Lyu et al. (2015). This framework consists of a master UAV which leads and controls multiple slave UAVs. Both master and slaves are equipped with downward cameras to obtain rectified images of the ground. The visual servoing is achieved by using the moment of the SIFT features. Where the extracted SIFT features by the master UAV are matched with the features extracted by the slave UAVs. Afterwards, the moment feature is generated. Finally, based on the obtained information, a visual servoing controller is applied to guide the slave UAVs to follow the master UAV. However, all the results are obtained by simulations.

4. Vision-based autonomous applications for UAVs

The fields of computer vision and image processing have shown a powerful tool in different applications for UAVs. Autonomous UAVs applications are an interesting area, but at the same time are considered as a challenging subject. Among these applications, this literature throws light on the autonomous applications for take-off and landing, surveillance, aerial refueling, and inspection as shown in Table 4.

4.1. Autonomous landing

Autonomous Take-off and Landing is a fundamental task not only for VTOL vehicles (Cocchioni, Mancini, & Longhi, 2014; Gautam, Sujit, & Saripalli, 2014) but also for fixed wings UAVs (Huan, Guoliang, & Jianqiang, 2015; Keke, Qing, & Nong, 2014). For vision-based take-off and landing, different solutions have been proposed in order to deal with this problem (Costa, Greati, Ribeiro, da Silva, & Vieira, 2015; Herissé, Hamel, Mahony, & Russotto, 2012; Lee et al., 2014b; Xiang, Cao, & Wang, 2012).

Wenzel *et al.* introduced a solution using Wii IR camera (Wenzel, Masselli, & Zell, 2011). The concept of this approach is to detect four lights LEDs pattern situated on a mobile robot. However the system is able to track the landing pattern, but the use of IR camera has several limitations; such as that the system cannot be applicable in outdoor flights because of the sensor sensibility to the sunlight. Furthermore, the system has maximum detection region up to 2.5 m because of the limitation of the IR cameras. Another vision-based cooperation between a UAV and an Unmanned Ground Vehicle (UGV) has been presented in Hui, Yousheng, Xiaokun, and Shing (2013). At which, RGB camera is used to detect the landmark. This approach used Hough Transform to detect 20 cm radius circular landmark attached to the mobile robot. Then the detected circle is restricted by a square shape in order to estimate the center. Finally, a closed-loop PID is applied to perform the control of the UAV.

Multi-scale ORB method (Rublee, Rabaud, Konolige, & Bradski, 2011) integrated wsith the SLAM map to detect the landing site has been presented in Yang et al. (2013). Although the experiments have shown good results, this method is dependent on the map generated from the SLAM, and consequently loses its accuracy in the case of the absence of the map.

4.2. Autonomous surveillance

Surveillance based on aerial imaginary is one of the main applications that takes advantages of UAVs in both military and civil areas. Different methods and approaches have been presented to optimize the solution of the surveillance in terms of time, number of UAVs, autonomy, etc. Freed, Harris, and Shafto (2004) presented an evaluation approach, comparing the performance of the methods and algorithms that employed the UAVs for autonomous surveillance tasks with the guidance of human operators. Recently, a study based on the nature of the tasks and the capabilities of the UAVs has been presented in Cusack and Khaleghparast (2015). In this evaluation study, a scheme comparing different small UAVs has been proposed; in order to select the adequate UAV that provides the high performance and safety to improve the traffic conformance intelligence.

A feature-based approach for detecting and tracking multiple moving targets from UAVs was presented in Siam and El-Helw (2012). First, the features are extracted using Harris detector, then the pyramidal LK optical flow model and the LMEDS are used in order to classify the movement of the detected features. Finally, a Kalman filter and a template matching algorithm are used to track the detected targets.

UAV–UGV cooperation scheme for autonomous indoor surveillance tasks has been presented in Saska, Krajník, and Pfeucil (2012). In this system, both vehicles are based on visual information for navigation, localization and landing (UAV). In addition to the helipad that carries the UAV, the UGV is equipped with the sensors necessary for the surveillance tasks. Based on Speeded Up Robust Features (SURF) detector, the UGV can detect and track the landmark features from the input images and estimate its location, then move autonomously along predefined waypoints. Once the UGV reaches to an inaccessible location, the UAV flies from the UGV and starts the aerial inspection task. Finally, by using color detection algorithms, the UAV locates the helipad pattern and performs the autonomous landing.

Dealing with the mission planning problem for multiple UAVs, Geng, Zhang, Wang, Fuh, and Teo (2013) proposed an approach that provides continuous surveillance operations. This approach is divided into two phases. The first phase addresses the search of the locations of the cameras to provide the complete coverage of the targets in the area. To achieve this, a Genetic Algorithm (GA) is implemented to obtain the optimal solution. The second phase deals with distributing the selected locations that are obtained from GA over a number of UAVs, and creating the paths to be followed in the surveillance. Ant Colony System (ACS) algorithm is used to find the solution for the paths and endurance. However, the experiments have been limited to simulations.

Application	Description	Purpose	Related work
Autonomous Landing	Take-off and Landing	VTOL	(Costa et al., 2015; Huan et al., 2015; Jung et al., 2015) Herissé et al. (2012); Lee et al. (2014b); Yang et al. (2013) (Beck et al., 2016; Casau, Cabecinhas, & Silvestre, 2011; Wenzel et al., 2011)
		Fixed Wing	(Daibing, Xun, & Weiwei, 2012; Kim et al., 2013; Kong, Zhang, & Zhang, 2015; Kong et al., 2014; Muskardin et al., 2016; Pan, Hu, & Shen, 2015; Pouya & Saghafi, 2009)
Autonomous Surveillance	Using aerial imaginary for monitoring and vigilance purposes	Traffic	(Cusack & Khaleghparast, 2015; Heintz et al., 2007; Ke et al., 2015; Kim et al., 2012)
		Agricultural crop	(Anthony et al., 2014; Navia, Mondragon, Patino, & Colorado, 2016; Tokekar, Hook, Mulla, & Isler, 2016)
		Animal protection	(Ward, Hensler, Alsalam, & Gonzalez, 2016; Xu et al., 2015)
		Other	(COE, 2016; Semsch et al., 2009)
Aerial Refueling	Refueling the aircrafts during the flight by using a tanker aircraft	Boom-and-Receptacle	(CHEN, JIA, & ZHANG, 2010; Mammarella et al., 2010; Williamson et al., 2009; Yuan, Yan, Qu, & Zhao, 2015c),(Haibin Duan & Qifu Zhang, 2015; Yaohong, Jizhi, Qichuan, & Jing, 2013; Yuan, Whidborne, & Xun, 2014)
		Probe-and-Drogue	(Bai, Wang, Yin, & Xu, 2014; Mati, Pollini, Lunghi, Innocenti, & Campa, 2006; Ruiz, Martin, & Ollero, 2015; Wu, Zhang, Xu, Zhou, & Luo, 2013) (Martínez, Richardson, & Campoy, 2013; Su, Wang, Shao, & Yao, 2015; Xufeng et al., 2013)
Inspection	Inspecting the damages and collapses in the structures for monitoring and maintenance purposes	Buildings	(Choi & Kim, 2015b; Eschmann et al., 2012; Nikolic et al., 2013; Omari et al., 2014)
		Bridges	(Chan, Guan, Jo, & Blumenstein, 2015; Hammer, Dumoulin, Vozel, & Chehdi, 2007; Metni & Hamel, 2007)
		Wind turbines	(Høglund, 2014; Stokkeland, 2014; Stokkeland et al., 2015)
		Power lines	(Araar & Aouf, 2014; Benitez, Bogado, Guerrero, & Arzamendia, 2016; Cao, Zhu, Han, Wang, & Du, 2013; Du & Tu, 2011)
Search and Rescue	Gather information in disaster and hazardous sites		(Agcayazi, Cawi, Jurgenson, Ghassemi, & Cook, 2016; Naidoo, Stopforth, & Bright, 2011; Tao & Jia, 2012) (de Araujo, Almeida, Miranda, & de Barros Vidal, 2014; Erdos et al., 2013)
Mapping	Collecting topographical, thematic and geospatial data		(Fraundorfer et al., 2012; Hackney & Clayton, 2015; Tampubolon & Reinhardt, 2014) (Cui et al., 2007; Gotovac, Gotovac, & Papić, 2016; Li & Yang, 2012; Navia et al., 2016), (Ahmad et al., 2013; Ma et al., 2013; Pérez-Ortiz et al., 2016; Ying-cheng et al., 2011)

4.3. Autonomous aerial refueling

Autonomous Aerial Refueling (AAR) describes the process of air-to-air refueling, or in other words, in-flight refueling. AAR is divided into two main techniques (Li, Mu, & Wu, 2012a), the first one is Boom-and-Receptacle Refueling (BRR), in which a single flying tube (boom) is moving from the tanker aircraft for connecting the receptacle that is situated in the receiver aircraft. The second technique is the Probe-and-Drogue Refueling (PDR), in which, the receiver releases a flexible hose (drogue) and the tanker maintains its position to insert the rigid probe into this drogue. Fig. 3 shows the concept of the two types of the AAR system. AAR is very critical operation and usually the tanker pilot has to be well trained to perform these complex operations. On the other hand, in UAVs, the remote controlling for AAR operation increases the complexity of the task. Different techniques use GPS and INS to obtain the relative pose of the tanker with respect to the receiver aircraft. However, these techniques have drawbacks: First, in certain cases, the GPS data cannot be obtained, especially when the receiver aircraft is bigger than the tanker, and prevents the connection with the satellites. The second drawback is the integration drift of the INS. On the other hand, the vision-based methods proposed an alternative or complementary solution for AAR. Different studies and surveys of vision -based methods and approaches for AAR that are used with UAVs have been introduced in Mammarella, Campa, Napolitano, and Fravolini (2010), Li et al. (2012a), Aarti and Jimoh O (2013).

In Xufeng et al. (2013), a machine vision approach has been presented to provide a solution for PDR technique. At which, the features are detected and extracted from Hue, Saturation, and Value (HSV) color space images. Then the least square ellipse fitting model is applied to the detected features to find the center of the drogue. From their experiments, it has been shown that the using of HSV color space increases the accuracy of the feature extraction step.

On the other hand, Deng *et al.* developed a system of the BRR technique for the AAR based on stereo vision (Deng, Xian, & Duan, 2016). At which, the tanker is provided with a binocular camera in order to detect the color characteristics of the markers. Then the system estimates the position of the contacting point of the boom to the receptacle. Although the system showed good results of the marker detection phase in the outdoor experiments with different light conditions, but also, it needs improvements in the binocular measurements to increase the stability and the accuracy of the pose estimation of the receptacle for the docking phase.

Recently, a visual framework for AAR has been presented in Yin et al. (2016). At which, two classifiers have been combined for the detection and tracking of the drogue. The D-classifier is used to detect the drogue from the input images. In addition, the T-classifier is used to track the detected drogue. Although the results showed better performance, the system has a limitation in the time of computation which is not suitable for real-time operations.

4.4. Autonomous inspection

Aerial Inspection is one of the most recent and in demand applications that takes the advances of the UAVs (especially rotorcrafts). Along with the safety and the decreasing of human risk, UAVs has the advantage of reducing operational costs and time of the inspection. However, it is important to keep the image stability against any kind of maneuver (Cho, Ban, & Kim, 2014). UAVs can perform inspection tasks in different terrains and situations; such as buildings, bridges (Metni & Hamel, 2007), wind turbines, power plant boilers (Burri, Nikolic, Hurzeler, Caprari, & Siegwart, 2012), power lines (Du & Tu, 2011), and even tunnels.

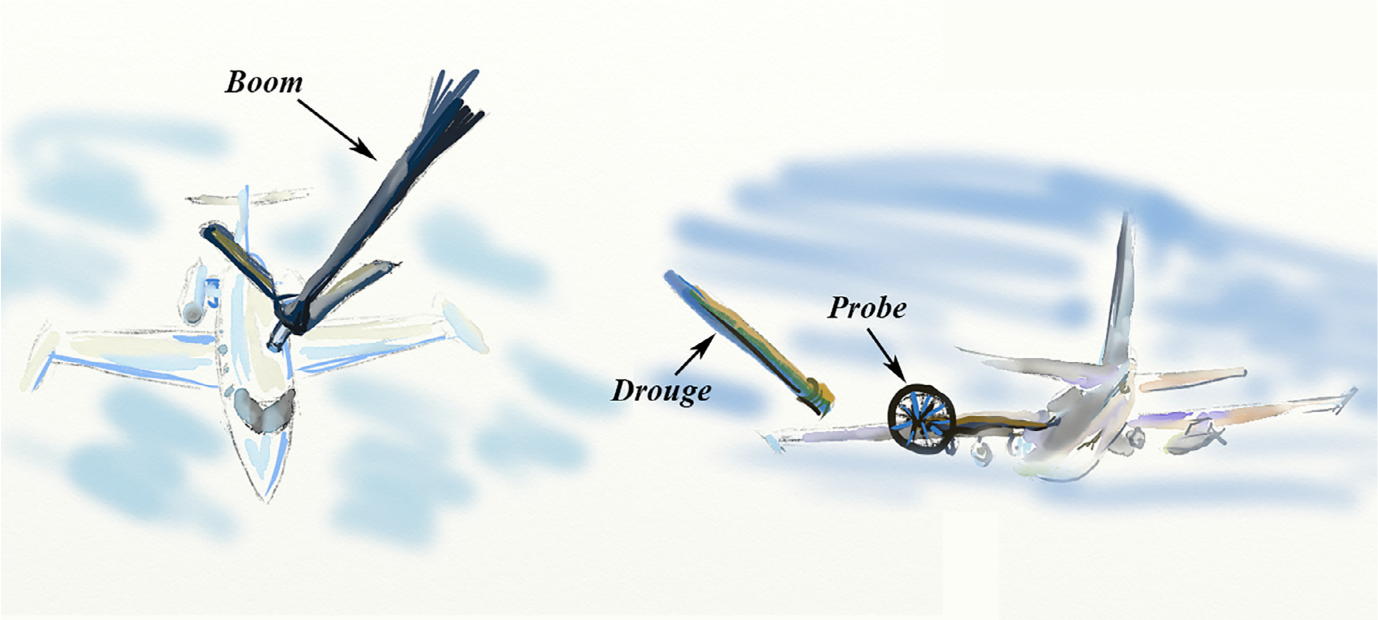

Fig. 3. Aerial Refueling techniques.

An integrated visual-inertial SLAM sensor has been proposed in Nikolic et al. (2013) in order to be used with the UAVs for industrial facilities inspection purposes. This system consists of a stereo camera and MicroElectroMechanical System (MEMS) gyroscopes and accelerometers. The UAV performs autonomous flights following predefined trajectories. The motion of the UAV is mainly estimated by the inertial measurements; then it is refined using the visual information. From the experiments, it has been shown that the system suffers from a delay between the inertial sensors and the stereo camera. Thus, a calibration process is required. In addition, the results showed a drift error of 10 cm in the displacement over time. Another visual-inertial sensor has been introduced in Omari, Gohl, Burri, Achtelik, and Siegwart (2014). At which, a visual-inertial stereo camera is used to estimate the pose of the UAV as well as to build a 3D map of the industrial infrastructures while inspection.

In Araar and Aouf (2014), two visual servoing approaches were presented for power line inspection purposes. Both approaches dealt with the problem of keeping the UAV with a close and determinate distance to the power lines while performing the inspection. In the first approach, an IBVS formulation has been combined with the Linear Quadratic Servo (LQS) to improve the control design of the UAV. While in the second approach, the control problem was solved using the Partial Posed Based Visual Servoing (PPBVS) model. As it has been shown from their experiments, the PPBVS is more efficient and more robust than the IBVS. However, PPBVS approach is very sensitive to the calibration errors.

Autonomous UAV for wind turbines inspection has been presented in Stokkeland, Klausen, and Johansen (2015), Høglund (2014). First, the Global Navigation Satellite System (GNSS) and altimeter are used for positioning the UAV in a determinate distance from the tower, then the UAV are rotated to face the hub using the visual information. These works are based on Hough Transform to detect the tower, the hub, and the blades. The only difference is in the tracking phase where in Stokkeland et al. (2015) the Kalman filter is used to track the center of the hub, while in Høglund (2014), the tracking is based on optical flow algorithms, then the motion direction, velocity and distance of the hub and the blades can be estimated. Finally, the UAV flights in a preprogrammed path in order to perform the inspection task.

5. Conclusions

In this paper, vision-based systems for UAVs have been reviewed as a whole methodology to cope with cutting-edge UAV technology, where environment perception has been studied as a complex and essential task for UAV navigation and obstacle detection and avoidance in the last decade. The advantages and improvements of computer vision algorithms towards the presented reliable solutions have been presented through real results under demanding circumstances, such as, pose estimation, aerial obstacle avoidance, and infrastructure inspection. So, complex tasks and applications have been analyzed and difficulties have been highlighted, where the trustable performance of the vision-based solutions and the improvements in relation to the previous works of the literature are provided.

The different vision-based systems mounted in an UAV represent actual applications and help to overcome classical problems, such as research works performed by authors, like autonomous obstacle avoidance or automatic infrastructure inspection, among others. So, the strengths of the presented computer vision algorithms for UAVs have been clearly stated in the manuscript. However, presented applications have specific drawbacks that should be taken into account. That is, the vision-based systems are low cost sensor devices, which provides high amount of information, but have the drawback of the high sensitivity to lighting conditions (e.g. direct sun light may lead to lack of information). Moreover, all the presented algorithms and applications give full understanding and convergence to the next generation of UAVs.

The presented survey provides a full review of the vision-based systems in UAVs in the last decade, including author's works in this field, which contributes to the full understanding of novel applications derived from them, and fosters the development of outstanding UAVs that are capable of the most advanced and modern tasks in the most challenging scenarios.

Future work will focus on mainly in optimizing the computer vision algorithms by intelligent mechanisms based on knowledge and refined data. Secondly, the improvement of the real-time capabilities of the algorithms and on-board data fusion constitute the key point of the intelligent systems in Unmanned Aerial Vehicles. The third future work pass by the injection of flying knowledge and automatic maneuvers in the on-board knowledge-based systems, in order to enhance the accuracy of the decision-making methods in UAVs to complete a global flying mission.

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