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Unmanned Aerial Vehicle-based Traffic Analysis: A Case Study to Analyze Traffic Streams at Urban Roundabouts

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Abstract

Recently, multirotor Unmanned Aerial Vehicles(UAVs) or drones have become increasingly popular for a vast variety of civil applications. Efficient traffic data collection and extraction of various flow parameters are some of the futuristic applications of this technology. However, such applications still need to be streamlined and thoroughly explored for varying traffic and infrastructural conditions. In this paper, the focus is on the authentication of the application of small multirotor UAVs for traffic data collection and subsequent analysis of traffic streams at urban roundabouts. This paper presents an analytical methodology to evaluate the performance of roundabouts by extracting various parameters and performance indicators. The performance evaluation methodology is based on: (i) determining traffic volume via OD matrices for each leg, and (ii) analyzing drivers' behavior via gap-acceptance analysis. The overall analytical process is principally based on the authors' previously proposed automated UAV video-processing framework for the extraction of vehicle trajectories. The extracted trajectories are further employed to extract useful traffic information. The experimental data to analyse roundabout traffic flow conditions was obtained in the city of Sint-Truiden (Belgium). The results reflect the value of flexibility and bird-eye view provided by UAV videos; thereby depicting the overall applicability of the UAV-based traffic analysis system. With the significant increase in the usage of UAVs expected in the coming years, such studies could become a useful resource for practitioners as well as future researchers. The future research will mainly focus on further extensions of the UAV-based traffic applications.

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Keywords: Unmanned Aerial Vehicles(UAV);Drones;Traffic Data Collection;Traffic Analysis;Roundabout Traffic;Vehicle Trajectories

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1. Introduction

The efficient management and control of ever-increasing traffic volumes and congestion levels, has become one of the most critical challenges faced by municipalities and governments all over the world. This problem further magnifies particularly at urban intersections where a high number of conflict points emerge, leading to road safety as well as capacity issues. In this regard, roundabouts provide an efficient alternative for managing traffic at at-grade intersections[1,2]. Roundabouts are basically circular intersections with specific design and traffic flow priorities. The circulating traffic is given priority over the approaching traffic, hence ensuring a smooth and safe flow of traffic. Based on these priority rules, the roundabouts can also be termed as a series of T-junctions which have their own drawbacks[3]. Therefore, it is critical to analyze and evaluate the roundabout performance, particularly in urban environments, in order to ensure smooth traffic operation. However, for this purpose, an accurate, dynamic and quickly generated traffic data is required[4].

The collection of traffic data is usually an expensive and cumbersome process, depending majorly on the employed method and the required level of detail. In the past decades, the majority of the traffic data collection has been done using the traditional sources e.g. manual counters and observers, induction loops, stationary video recorders etc. However, these equipment produce extremely limited 'point' data which cannot be used to estimate complex traffic flow phenomenon such as the process of accumulation and dissipation of queues. In addition to this, the emergence of hidden points in the study area further limits the scope of the study[5,6]. Particular, fixed video camera-based studies face a huge problem of occlusion in which the objects of interest are hidden either partially or completely behind other objects e.g. trees, trucks etc. Although, this problem can be solved technically by increasing the number of cameras/sensors or manual observations[7], the increased expenses and workforce deem it practically unfeasible. On the other hand, advanced ITS data collection technologies e.g. vehicle-to-infrastructure (V2I), probe vehicles with GPS and other smartphone sensor technologies have also been employed in recent years. These technologies provide detailed and dynamic traffic data, however they result in big datasets which are difficult to handle especially in a short time span[8]. Additionally, such technologies might influence the actual behavior of the travelers since they already know they are being observed[6,9]. Another alternative for traffic data collection is the aerial photography or remote sensing. Satellites and manned aircrafts have been used over the years for dynamic traffic data collection. These technologies provide wide field-of-view and unbiased data, however cost and deployment issues restrict their practical employment. Recently, unmanned aerial systems (UAS) have started to gain popularity for traffic monitoring, management, and control purposes [5,10].

Small Unmanned Aerial Vehicles (UAVs), commonly termed as drones have become popular for a large variety of civil applications, ranging from survey of crop fields to parcel delivery applications[11,12]. In the past few years, this technology has also been identified to be useful in various transport management and planning applications.. UAVs are being used to observe, analyze and evaluate the traffic flow as well as safety conditions[5,10,13]. Traditionally, only the fixed-wing UAVs were employed for traffic monitoring purposes, however, in recent years the small rotary-wing type UAVs have also been used for traffic-related applications[14]. This non-intrusive and low-cost technology has improved rapidly and is now capable of providing high-resolution data (both in space and time) that can be used to extract vehicle trajectories and estimate traffic parameters. The UAVs can be particularly useful for data collection at sub-urban or such areas in the network where the installation of fixed sensor infrastructure is not viable. The key characteristics of this technology are its flexibility and the bird-eye view of the area of interest[11]. However, this is a recent technology and the actual applications, particularly for traffic data collection have not yet fully developed[5,6]. Therefore, there are some concerns and restrictions attached to this technology as well, such as limited battery time, safety concerns etc. All these concerns have to be coped with in the coming years. In order to streamline the processes involved in the application of UAV technology in traffic analysis, a universal guiding framework was proposed by Khan *et al*[11]. Additionally, a detailed methodological framework for the automated UAV video processing and vehicle trajectory extraction has been presented by Khan *et al*[4].

In this paper, the emphasis is on the traffic flow analysis of vehicle trajectories extracted via small rotary-wing UAV footage. The experimental data to analyze traffic flow conditions was obtained over an urban compact roundabout situated in the city of Sint-Truiden (Belgium). This paper presents an analytical methodology to evaluate the performance of a roundabout by extracting various parameters and performance indicators. The performance evaluation methodology is based on: (i) determining traffic volume via OD matrices for each leg, and (ii) analyzing drivers' behavior via gap-acceptance analysis. The paper constitutes of an in-depth analysis of the roundabout traffic streams. In the coming years, the use of UAVs is expected to rise significantly. In this scenario, such analytical studies based on an automated systematic framework could serve as a reference for practitioners and researchers alike.

This paper is structured as follows: firstly, the existing literature is discussed concisely. The methodology section consists of a brief description of the UAV video processing and trajectory extraction framework along with the presentation of the roundabout flow analysis methodology. In the next section, a Belgian case study is presented to support the proposed methodology. This includes applications of extracted vehicle trajectories for traffic flow analysis. Lastly, a brief conclusion along with some discussions regarding the limitations and planned future works is presented.

2. Related Work

As found in the existing literature, UAVs are being researched upon for a wide range of applications, including traffic management, monitoring and analysis. Various researchers summarized the current research trends around the world regarding the use of UAVs for traffic surveillance and analysis applications[5,10,12,13].

Numerous UAV-based studies specifically for traffic analysis have been conducted in the previous few years. These studies can be classified based on 2 factors i.e. (i) type of equipment used, and (ii) type of video processing technique used. In the early years, mostly fixed-wing UAVs were used for traffic-related applications[7] whereas recently, many researchers have employed small multirotor UAVs for their experiments[4,6,9,14]. Similarly, studies depending on the video processing technique can be broadly classified into 2 types i.e. (i) Manual or Semi-Automatic studies and (ii) Automatic studies. Studies employing the semi-automatic approach are highly accurate, but are time-consuming and laborious as the object has to be detected and tracked manually for a number of frames[6,9,15]. On the other hand, the automatic approach promises a quick processing and analysis procedure; ultimately leading to the real-time analysis of the UAV acquired data. Recently, the number of studies based on automated approach have increased[4,16–19]. The authors have been attempting to extract various traffic parameters and vehicle trajectories in an automatic environment by using state-of-the-art object detection and tracking algorithms.

A lot of research has been conducted to analyze roundabout traffic flow using data acquired from different sources. St Aubin *et al*[1] employed traffic data from a fixed video camera system to analyze driver behavior at roundabouts in Canada. The authors extracted various traffic parameters by interpreting vehicle trajectories. Similarly, Mussone *et al*[20] have attempted to analyze roundabout performance by applying image processing techniques on fixed video camera data. All these studies have devised and demonstrated various ways to evaluate the performance of roundabouts. However, all of the existing studies mentioned up till now have been principally based on the fixed video camera systems, which generally produce data with high occlusion rate. Recently, few researchers have employed UAV-acquired data to conduct roundabout traffic flow and safety analyses studies. Salvo *et al*[21] have analyzed driving behavior using UAV videos at an urban roundabout in Italy. The authors conducted a gap-acceptance analysis for vehicles entering the roundabout. Similarly, same authors (Salvo *et al*[15]) have also conducted gap-acceptance analysis for an urban intersection using UAV data. Additionally, Guido *et al*[22] and Apeltauer *et al*[16] have evaluated the accuracy of roundabout traffic data obtained via UAVs.

3. UAV Video Processing and Analysis Framework

The traffic video data obtained via UAV has to be efficiently processed in order to conduct the desired traffic analysis on it. For this purpose, a UAV video processing and traffic analysis framework is presented which consists of an in-depth description of the steps involved in the systematic usage of the UAV-based traffic data. The UAV video processing framework for the automatic extraction of multi-vehicle trajectories has been presented in detail by Khan et al4. The processing framework is categorized into five modules i.e.: (i) pre-processing, (ii) stabilization, (iii) geo-registration, (iv) vehicle detection and tracking, and (v) trajectory management. The processing module is then followed by the traffic analysis module in which the trajectory dataset is used as an input. Figure 1 illustrates the components of the UAV based traffic video data processing and traffic analysis framework. All the modules of this framework are elaborated in detail in the previous research4. However, in this paper, only an overview of the UAV video processing framework is included.

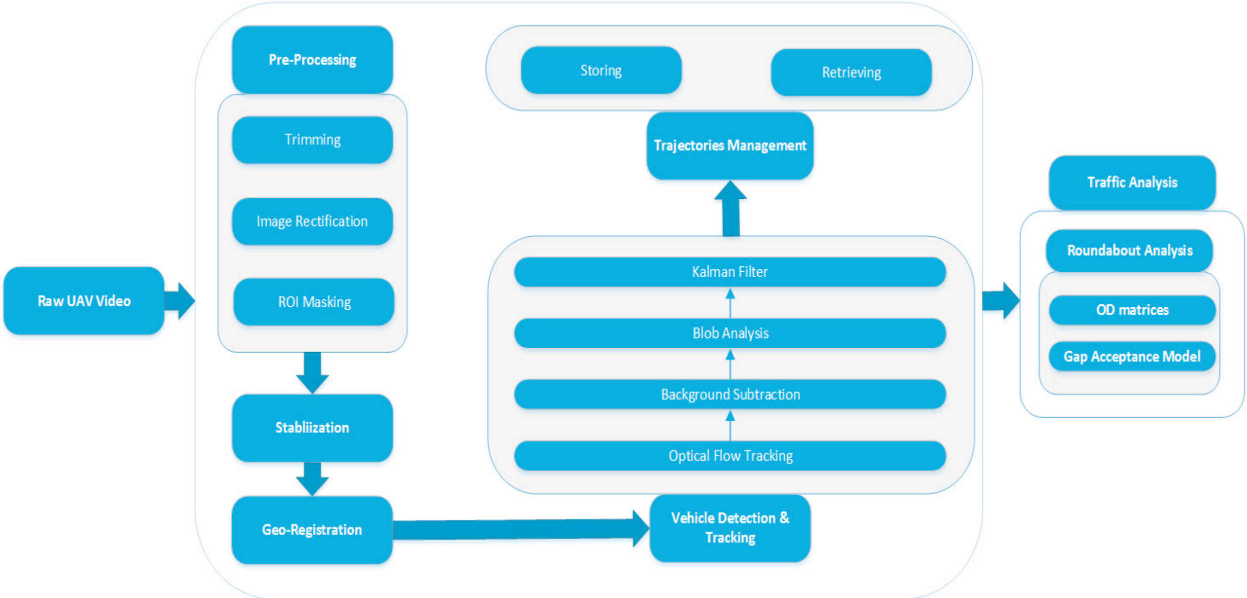

Fig. 1 The UAV video processing and traffic analysis framework

Firstly, the UAV videos are preprocessed by removing or minimizing the undesirable aspects of the recorded video. This step is followed by the video stabilization and geo-registration of the UAV-acquired traffic videos. The stabilization step is critical to minimize the level of instability or shakiness in UAV videos, as even a slight vibration of the camera can affect the accuracy of the extracted data. Further, the geo-registration or geo-referencing process ensures an efficient conversion of the UAV acquired mono-vision 2D image coordinates into a real-world coordinate system in order to enhance the applicability of the extracted vehicle trajectory data. Once the UAV images are geo-referenced or calibrated to a specific coordinate system, the next step is the automatic detection and tracking of vehicles of interest. The efficiency and accuracy of this process is critical in order to obtain a reliable and consistent set of trajectory data. The stabilized and calibrated UAV videos are fed into the detection and tracking module which constitutes of a number of sub-modules as indicated in Figure 1. The vehicles in motion are detected and tracked via a series of algorithms implemented in C++ (OpenCV library). Moreover, the extracted trajectory dataset is stored and managed in order to utilize it efficiently for further traffic analysis. The processing of UAV videos is then followed by the traffic analysis module in which the resulting trajectories are employed to extract useful traffic information. In this paper, the capacity and flow analysis of roundabout traffic is conducted by estimating various parameters and performance indicators. More specifically, the UAV-acquired traffic data is utilized to generate OD matrices for different legs of the roundabout by placing virtual counters for each entry and exit point. The algorithm for these virtual counters is implemented in visual C++ and the computer vision library OpenCV. Additionally, the waiting times and critical gaps for the vehicles entering the roundabout are also calculated. The following sections will elaborate the detailed analytical process via a case study.

4. Case Study

As mentioned earlier as well, the main aim of this paper is to demonstrate the potential applications of UAVs or drones for traffic analysis and management, particularly in the scenario of urban roundabout flow analysis. In this section, a detailed case study is presented in order to validate the practicality of the UAV-based traffic data collection, processing and analytical framework. The data collected via UAV flights is used for analyzing traffic volume and capacity by generating origin-destination(OD) matrices. Additionally, the extracted data is also used to analyze drivers' behavior via gap-acceptance study. The following sub-sections present an in-depth description of the whole experiment and the analytical process:

4.1. Experiment Specifications

In order to obtain an experimental dataset for the validation of the proposed analytical framework, a series of UAV flights were conducted in the urban commercial area of the city of Sint-Truiden (Belgium). An urban compact roundabout was selected as the area under observation. The location as shown in Figure 2 is a busy urban commercial area, having a football stadium and rail-station in the vicinity. The selected roundabout consists of single-lane approaches from each side, whereas one leg also has a right turning lane just before the roundabout in order to minimize the traffic flowing into the roundabout. A detailed flight planning process was carried out before the actual conduction of the flights. The UAV flights were conducted in order to capture the early-evening rush hour on a Friday afternoon (15:00 to 16:30 hours). Importantly, the weather and wind conditions were perfect for the UAV flights i.e. mostly clear skies with gentle wind level (18km/hour, Beaufort scale 3).

Fig. 2 The UAV view of the studied roundabout (left-side); and Google Earth satellite image of the roundabout(right-side)

A series of UAV flights were conducted using a custom-built high-end octocopter UAV i.e. Argus-One (from Argus-Vision) with an attached Panasonic Lumix GH4 DSLM camera. The main focus for the experiment was to obtain a high-quality experimental data with a minimal setup time. The equipment as shown in Figure 3 has a relatively low flight time of around 10 minutes, but provides an extremely stable and high resolution (4K@25fps) video data. Additionally, an attached live-feed transmission system allowed to optimize the camera angles for the best view of the roundabout area during the flight. The UAV was hovered i.e. maintaining a constant altitude with zero velocity, over the study area at 80m and 60m heights. The series of UAV flights resulted in a nearly 15-minute useful traffic video after trimming the take-off and landing maneuvers of the UAV. It is also important to mention here that the analysis of UAV traffic videos was done on an Intel® Core™ i5-4210M CPU at 2.60 GHz, with 4-GB RAM.

Fig. 3 The Argus-one UAV (left-side); and Google Earth satellite image of the studied intersection(right-side)

4.2 Roundabout Traffic Analysis

The UAV traffic video data can be employed to extract useful traffic information required for analyzing traffic flow. This paper presents an analytical approach, specifically aimed to evaluate the performance of an urban roundabout. The performance evaluation methodology is based on: (i) quantifying traffic volume via OD matrices for each leg, and (ii) analyzing capacity and drivers' behavior via gap-acceptance analysis.

The volume of the traffic flowing through the roundabout is a good indicator of the performance of a roundabout. The Origin-Destination matrices are commonly used tools for planning and studying various road infrastructural elements, particularly roundabouts. These matrices help in quantifying and analyzing traffic movement through each leg of the roundabout. In order to determine the traffic volume, a virtual counter is placed on each leg of the roundabout. These virtual counters provide an accurate sum of vehicles entering or leaving the roundabout. Figure 4 shows the counters and OD matrices for the study area. As indicated in Figure 4, maximum traffic originates from the main city(counter 7) and flows majorly into surrounding shopping and residential area(counter 4). It is also worth mentioning that the automatic traffic counts were verified by manual counts and only a negligible amount of error was detected, specifically in case of vehicles partially occluded by close-by trees.

		Destination				
	Counters	2	4	6	8	Total
Origin	1	25	27	20	0	72
	3	0	7	26	12	45
	5	1	4	33	36	74
	7	19	61	0	19	99
	Total	45	99	79	67	

Fig. 4 Position of virtual counters at roundabout approaches; and the Origin-Destination(OD) matrix for the roundabout traffic

Apart from traffic counts, the analyses of capacity and actual drivers' behavior are important aspects employed for traffic modeling and management. Various measures of effectiveness(MOEs) e.g. waiting time, queue lengths, gap acceptance/rejection are used to evaluate the infrastructure performance and determine level-of-service. Gap-acceptance model is commonly used not only to estimate the capacity but also to study drivers' behavior while merging or crossing another traffic stream. The primary parameter used in gap acceptance modeling is the critical gap. The critical gap is defined as the minimum time gap between consecutive vehicles circulating inside the roundabout that allow waiting vehicles on an approach to enter the roundabout23. The average value of critical gap and follow-up-time is taken as 4.5 sec and 2.7 sec (60% of the critical gap) respectively in the HCM 201024. The estimation of the critical gap is done using Modified Raff's method25,26, which utilizes both the accepted and rejected gaps. Table 1 shows the number of gaps accepted or rejected by merging drivers for each time gap level.

Table 1. Number of Gaps Accepted and Rejected according to different Time Gap Intervals (seconds)

Time Gap (seconds)	Number of Accepted Gaps	Number of Rejected Gaps
< 1	0	4
1-2	1	15
2-3	4	19
3-4	5	2
4-5	7	0

As evident from data in Table 1, the number of gaps accepted and rejected are inversely proportional to each other. According to modified Raff's method, the critical gap can be calculated by determining the intersection point of the gap accepted and rejected plots. Figure 5 illustrates the critical gap estimation approach and highlights the intersection point of the plots as the critical gap. The value of the critical gap for the experimental data is found to be approximately 3.83 seconds. This value is slightly less than the HCM 2010 specified average value of 4.1 seconds, reflecting the general driving attitude and also the level of service of the roundabout.

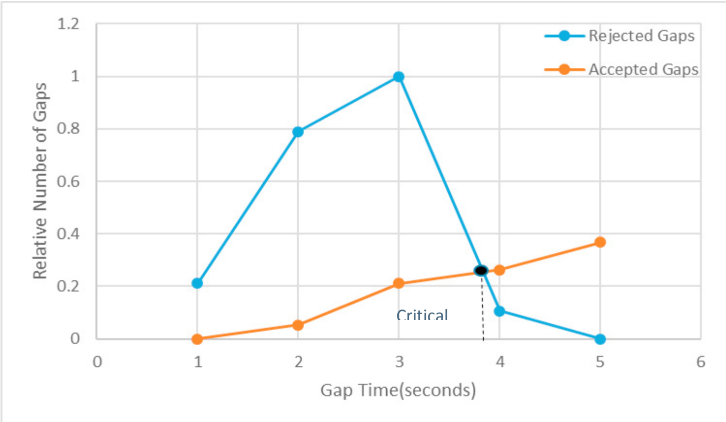

Fig. 5 The Critical Gap Estimation based on the Plots of Accepted and Rejected Gaps

5. Discussion & Conclusion

In this paper, a case study has been presented in order to validate the applications of UAVs for traffic analysis, particularly in the scenario of roundabout flow analysis. A framework is presented for processing as well as analysis of traffic data acquired via small UAV. The vehicle trajectories are extracted based on previously proposed automated UAV video processing framework[4]. In addition to this, a methodology to employ the resulting trajectories for roundabout traffic flow analysis is proposed in this paper. The roundabout performance evaluation methodology is based on: (i) determining traffic volume via OD matrices for each leg, and (ii) analyzing level-of-service and drivers' behavior via gap-acceptance analysis. Based on the collected experimental data, a number of performance indicators were estimated. The generation of OD matrices and the estimation of critical gap parameter help in analyzing the interrupted flow conditions at an urban single-lane roundabout. The results of the analysis reflect the value of the flexibility and the bird-eye view provided by the UAV videos. Additionally, the proposed methodological analysis conducted on such experimental data may serve as a proof-of-concept for the actual traffic-specific applications of the UAV-acquired data. Such studies can be of particular interest not only for researchers but also for practitioners and traffic experts responsible for transport planning and management operations.

Further improvements to the UAV-based traffic monitoring and analysis system will be made in the future work. Although, UAVs have been demonstrated to be highly effective in traffic applications, still there are some limitations attached with the current technology. This includes factors ranging from hardware and software to legal aspects, such as the limited flight time of small UAVs along with some other concerns regarding the safety of flight operations.

Additionally, some limitations also exist for the automated processing of the UAV videos. Depending on various reasons, false or missed detection errors can occur. All these factors need to be addressed in the future research in order to further optimize the use of UAVs for traffic data collection. Apart from it, the future research will also be focused on conducting a more detailed and comprehensive roundabout traffic analysis. Additionally, the prospects of real-time processing of UAV data will also be explored.

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