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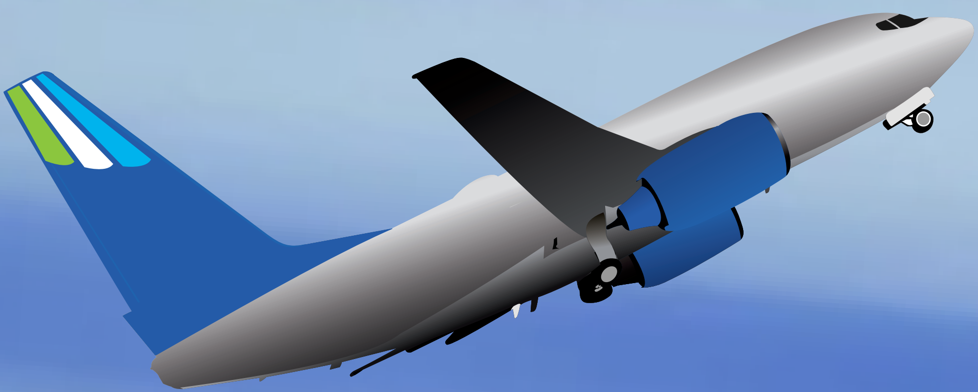
IJAST

International Journal of Aviation Science and Technology

Volume 1, Issue 2, December 2020



International Journal of Aviation Science and Technology

e-ISSN: 2687-525X

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Publisher	:	SARES International Sustainable Aviation and Energy Research Society
Licence holder	:	Prof. Dr. T. Hikmet Karakoç (President, SARES)
Address	:	Anadolu University TGBD TechnoPark Region No:210 26470 Eskisehir/Turkey

e-ISSN	:	2687-525X
DOI	:	10.23890/IJAST
Submission	:	www.ijast.org
e-mail	:	ijast@sares.org
Copyright	:	SARES Society

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International Journal of Aviation Science and Technology

Research Article

An Exploratory Study of Pilot Training and Recruitment in Europe

Lenard Mariyanov Adanov[1], Andrew Macintyre[2], Marina Efthymiou[3]*

[1] DCU Business School, Dublin City University, Dublin 9, Ireland
lenard.adanov2@mail.dcu.ie

[2] DCU Business School, Dublin City University, Dublin 9, Ireland
andrew.macintyre@dcu.ie

[3] DCU Business School, Dublin City University, Dublin 9, Ireland
marina.efthymiou@dcu.ie - 0000-0001-8611-5973

Abstract

Pilot training and recruitment is of fundamental importance for the aviation industry. Yet, a number of Commercial Pilot's License (CPL) applicants trained by Approved Training Organizations (ATOs) fail their airline assessments. To provide some clarity on why this is happening, we conducted in-depth interviews with twelve industry professionals and a detailed documentary analysis was undertaken. We found that the main reasons are: (1) Lack of preparation or technical knowledge; (2) Poor communication skills; and (3) Poor display of teamwork and leadership. The paper suggests that regulation should be implemented for ATO's to use screening processes on potential students to increase quality or Airline Pilot Standard Multi Crew-Cooperation (APS MCC) system, as an additional training system on top of what is being taught in ATOs. Regulations should further be linked with regular audits in place for smaller airlines to increase the effectiveness of their pilot assessments and recruitment processes in order to increase safety. Areas of further research as also identified.

Keywords

Pilot Training
Approved Training Organizations
Safety in Aviation
Aviation Regulation
Pilot Assessment
Pilot recruitment

Time Scale of Article

Received 27 July 2020
Revised until 27 October 2020
Accepted 5 November 2020
Online date 30 December 2020

1. Introduction

There has been extensive research into the global pilot shortage that was seriously affecting European airlines and the aviation industry as a whole [2, 7, 10]. There are many reasons for the pilot shortage including lack of financial resources to cover training costs for potential new trainees due to the high prices; high percentage of pilot attrition (retirement or death of captains); increased traffic growth; very difficult and strict entry assessments in both the medical and aptitude tests (for safety reasons); and many more.

Considering all the barriers in place already, which limit the supply of pilots, it is very worrying that many qualified pilots cannot get a job with an airline. Airline assessments throughout Europe are typically quite similar to each other in the steps, which are required to be passed by an interviewee pilot. These include passing Aptitude Tests such as the WOMBAT, or COMPASS [36], or one of the many other available on the market examinations [4, 18]. Then the pilots have to pass an Individual or Panel Interview, Group Exercises, Psychometric Evaluation or Personality Questionnaires, and finally the Aircraft Simulator. However, there is no official standard selection process for airline pilots' assessments. At this stage, the pilots would have already passed their entire 12-24 month training through an Approved Training Organization (ATO), also known as "flight schools", which includes 650 hours of theoretical study and 210 flight hours granting them a Frozen Air Transport Pilot License (ATPL, Frozen ATPL is given in Europe until the pilot has flown commercially for 1,500 hours at which point they receive their full ATPL

*: Corresponding Author Marina Efthymiou, marina.efthymiou@dcu.ie
DOI: 10.23890/IJAST.vm01is02.0201

Certificate) at the end. Otherwise, they could have chosen the Multi-Crew Pilot License (MPL) route which is the newest form of pilot training focusing on getting the pilot trained for a specific type of aircraft introduced by the International Civil Aviation Organisation (ICAO) in 2006. The MPL allows holders to exercise the privileges of the Frozen ATPL, but is limited to a certain aircraft type, certified for multi-pilot operation only. There is a lot of debate which way is better amongst aviation experts as the new MPL route is a lot more expensive considering the increase in time spent in the aircraft simulator though it is argued that it gives pilots a lot more hands-on knowledge to the specific aircraft they are being trained on [35].

Pilots also have a choice of going through their training in a modular or integrated fashion, meaning they could have it broken down and done part by part to be completed at their discretion and time or have it done in one full-time integrated course, known as Ab-Initio Training (from zero to pilot). After that, whether or not they took the ATPL or MPL route, they would have then completed their Type Rating Certification which takes up to another 2 months to finish. This means that before they sit their airline assessments, most pilots would have had to undergo roughly 2 years of training, costing up to €120,000 [11, 20], yet somehow, half of all those pilots fail some part of their final airline assessments. Having such a large percentage of the pilots who manage to not only overcome the financial barrier of entry, but also pass any preliminary assessments in the ATOs and the medical exams, to then fail to pass airline assessments securing them work in Europe is a serious problem that must be addressed.

The aim of this paper is to investigate why pilots fail in European commercial airline assessments and interviews, even though they have successfully passed training through official ATOs. More specifically this paper will:

1. Outline the current standards to which pilots are trained in ATOs.
2. Discover the minimum requirements for cadet pilot entries into Commercial Airlines.
3. Identify the key reasons for which 50% of pilots fail some airline assessments.
4. Give recommendations on how to improve the current pilot educational system.

The paper contributes to the body of knowledge by conducting research in an area significantly under-researched, but of importance to the airline industry especially considering the impact of COVID-19 on labour negotiation power.

The remainder of the paper is organized as follows. Section 2 begins by elaborating on the literature review associated with the pilot training. The methodology followed is outlined in Section 3. Section 4 outlines the results while Section 5 concludes the paper by providing some recommendations.

2. Literature Review

Research on the topic of Pilot Training is scarce and mainly led by practitioners rather than academics [19]. One source on the topic of Pilot Training is Captain Andy O'Shea, Chairman at European Aviation Safety Agency (EASA) Aircrew Training Policy Group (ATPG). He reported that only 48% of roughly 1000 candidates were found successful in the airline assessments of Ryanair. The analysis of huge amounts of data for the Competency-Based Training and Assessment element allowed the identification of competency weaknesses and planning of a course that addressed the weaknesses [26]. A potential solution to this is the enhancement of Multi Crew-Cooperation MCC to a standard [31]. This led to the implementation of the Airline Pilot Standard Multi Crew Cooperation (APS MCC) in 2016 [16]. This consequently contributed to an increased number of successful cadet applicants.

Recognizing the main challenges and weaknesses of pilots in these airline assessments, such as "Communication; Leadership and Teamwork; Problem Solving and Decision Making; and Workload Management" [31] meant that now it was known where the focus should be directed at.

Burns also discussed the issues newly trained pilots face when applying for jobs, as well as advice on the selection of pilot academies for budding pilots [8]. The Department of Transportation in Croatia published a study on the challenges sometimes found in training regiments within ATOs applying Root-Cause Analysis [3]. Some of the issues found were with inaccurate documentation due to some of the students not filling-in their required documents post-flight in time and either having to go back and fill them in from memory or having to input rough estimates. This resulted in under-prepared pilots once their training was complete and an extra step in the process to be implemented for pilot instructors to check the students' documentation was recommended.

Additionally on the issues of pilot training, there has been coverage by news organizations and specialized aviation societies. These have linked the challenges of pilot training and recruitment to the global pilot shortage, manufacturing constraints, and to the possible solutions available, including discussions on the introduction of the APS MCC [11].

In 2017, of the roughly 70,000 commercial airline pilots active in the European region [9], Irish Air Line Pilots Association (IALPA) estimates there are about 6,000 unemployed pilots in Europe today equal to approximately 8% unemployment [21]. Although 50% of new pilots fail certain airline assessments, they eventually find employment.

Multiple other studies have dealt with topics related to pilot errors, variance in pilot performance, pilots failing medical examinations, and flight safety once pilots are already within the airline [9, 27, 28]. Although these do not typically relate to challenges with pilot training and recruitment, a speculation is made that each of these would be intrinsically linked to how the pilots were trained before entering the airline and how they have upheld or improved their standards, though no concrete link can be made without a much larger study conducted. This will be examined in more detail in *Section 5.*

Current regulations by EASA on Aircrew Regulation and Training are set out and met by all ATOs before they can be granted with a license to be an ATO [15]. For the 50% failure rate at airline assessments to be what it is, this means that the minimum standards set out in EASA's regulation are not the same as some airline standards. Nevertheless, current safety standards in the aviation industry are indeed at an all-time high with the number of accidents resulting in fatalities being in a downward trend for several years now [24]. However, it is very much worth noting that the larger airlines with very strict airline assessments for flight crew have considerably better safety scores than smaller airlines. Not every airline's data on airline assessment failure rate is accessible, but most of the top airlines use similar if not the same type of assessments [4, 18]. This shows a probable correlation between those who have more lax assessments and a significant increase in filed safety reports – at least from the reports filed in the following Air Crash Investigation Units for 2019: AAIU [1], BEA [5], BFU [6], and DSB [14]. However, for causality to be confirmed, a much larger empirical study would need to be performed.

3. Research Methodology

Document analysis is a method commonly used in aviation [25]. For this specific topic, lack of statistics, record keeping, data protection and confidentiality imposed major difficulties. One of the key interviewees – Andy O'Shea- provided some data for Ryanair in this practitioner paper "The Challenges of Pilot Supply" that are presented in Section 4.

Due to the complexity of the topic, interviews with key experts were conducted to provide empirical evidence. The interview is a widely used research method in aviation that has been used in safety [25, 30], business and complex issues [33, 17].

Table 1 lists the interviewees of this study. When it came to the sample size, twelve seemed like a reasonable number providing for multiple people from each position to be interviewed to try and remove subjectivity even further by not relying anywhere on a single source (e.g. Three Heads of Training; Two Pilot Trainees, etc.) Due to the overwhelming benefits of face-to-face interviews, they were the predominant type used; however, due to limitations in availability, or due to several of the interviewees being in different countries, phone and video call methods also had to be used.

Finally, ethical guidelines and regulations were strictly followed. Giving everyone the choice to remain anonymous also ensured that fear of answering honestly was removed [29]. Only one interviewee chose to avail of this option.

Table 1: List of interviewees

Name	Title	Type
Karl O'Neill	Captain in Aer Lingus	Phone
Roy Forrest	Trainee at Atlantic Flight Training Academy	Phone
Andy O'Shea	Chairman of Aircrew Training Policy Group (ATPG) Ex-Head of Training and Deputy Chief Pilot of Ryanair	Face-to-Face
Margie Burns	CEO of Aviation Selection Consultants	Phone
Michael Ryan	Head of Training of BAA	Phone
Petter Hörnfeldt	Base Type Rating Examiner at Mentour 360 SL	Videocall
Darragh Owens	Head of Training at National Flight Centre	Phone
Douchan Stanulov	COO, Sofia Flight Training Academy	Face-to-Face
Stefan Stefanov	Head of Training, Sofia Flight Training Academy	Face-to-Face
Slav Adanov	Trainee at Sofia Lesnovo Academy	Face-to-Face
Anonymous	Captain at a Low-Cost Airline	Face-to-Face
Krasimir Kucarovy	Type Rating Instructor Examiner at Wizz Air	Face-to-Face

4. Analysis & Discussion

As mentioned in the previous sections, the fact that challenges with pilot training and recruitment do exist is irrefutable. The change in pass rates after the adoption of the APS MCC alone proves it to be true.

The standards to which pilots are trained in ATOs are set by EASA and ICAO regulations. ICAO regulation on the topic of training can be found in Annex 1 on Personnel Licensing [22]. This can mainly be split into two areas: Standards and Recommended Practices (SARPs) which the Annex above is, and Doc 9868 "Procedures for Air Navigation Services – Training" (PANS-TRG) which is not enforced, but acts as a recommendation, which relates to the responsibilities and guidelines in place for approved training organizations [23]. The main issue faced here is that many of the proposals in the PANS-TRG are in fact guidelines that ATOs can decide whether they are to be implemented and to what extent. Furthermore, since PANS-TRG are complementary to the SARPs and not mandatory, there is understandably a difference in the quality of ATOs with those who implement the extra steps, albeit probably cost more, and those who do not. Much like the choice of implementing the APS MCC system or not from the side of ATOs.

Reviewing application processes and consulting the interviewees, we found that the average or typical standards for airline assessments of the major airlines in Europe, such as Aer Lingus, Air France, EasyJet, Ryanair, Wizz Air, etc. are typically quite similar and follow the same recommendations from ICAO and EASA. Most airlines have listed as acceptable criteria the same minimums that ATOs are subjected to from these regulations. Yet 50% of the applicants to these airlines coming out of ATOs supposedly fail these exact assessments. This leads to the very important question of whether or not the minimum training required by regulation is even being met by some of these ATOs.

Interviewees Adanov and Kucarov stated that in some ATOs students would often not be tracked for the number of hours flown. Not all ATOs possessed GPS tracking software in their aircraft to monitor student flights and very few instructors verify the information students wrote down in their logbooks going back to the issues signalled by the Croatian Ministry of transport [3]. Furthermore, the approach given to the theoretical knowledge was looked at from the perspective of getting past it as quickly as possible as the evident culture at some ATOs seems to look at just passing the exam and then forgetting all the material covered until then soon after as confirmed by interviewees Adanov, Owens and Kucarov. Owens stated that "A lot of students come in and say "oh I will get the theory out of the way" and a lot of (ATO) courses are structured to re-enforce that message". The other factor leading to poor training from ATOs relates to the student-ATO relationship. O'Neill in his interview stated that he is concerned that the student pilots are resistant to getting honest feedback during their training and the ATO's receive pressure to treat them as customers that need to be satisfied.

The issue here is finding out if this is down to regulatory standards being too low; airline standards being too high; or if ATOs are failing to prepare students for what is expected of them; or if it is simply down to the students. Stating that students fail simply because in any exam there is a failure rate and it so happens that the one to become a pilot is very high seems to dismiss any possible underlying issue. Although there always are additional factors including performance in exam situations, these assessments are for pilots who are supposed to, if successful, work in very stressful situations where there may be moments of limited time to think and react to ongoing situations.

According to the interviewees, the main reasons for the 50% failure rate at the airline assessments were: lack of preparation or technical knowledge; poor communication skills; or poor display of teamwork and leadership. The first of these can be ameliorated by ATOs focusing on teaching the cadets only the theoretical knowledge and how it can be applied in their job as flight crew, and thus convert it to working and long-term memory according to Cowan [13].

Table 2. Comparison of ATO and Airline Minimum Requirement

	ATO Min. Training Reqs	Aer Lingus Reqs	Air France Reqs	easyJet Reqs	Ryanair Reqs	Wizz Air Reqs
Theoretical Knowledge	14 ATPL exams for EASA CPL	EASA CPL / Frozen ATPL	EASA CPL / Frozen ATPL	EASA CPL / Frozen ATPL	EASA CPL / Frozen ATPL	EASA CPL / Frozen ATPL
Language Proficiency	English Operational Level (Level 4)	English Operational Level (Level 4)	Fluency in French & English Ops. Level (Level 4)	English Operational Level (Level 4)	English Operational Level (Level 4)	English Operational Level (Level 4)
Experience	200hrs total|100hrs as Pilot-in-Command	M	200hrs	1000hrs|500hrs on a/c over 10T MTOW	100hrs as Pilot-in-Command	200hrs
Medical Examination	Class 1	Class 1	Class 1	Class 1	Class 1	Class 1
Validity to work in EU	M	Required	Required	Required	Required	Required
APS MCC-Training	Not required	M	M	M	Preferred	M
MCC Training Completed	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory	If applicable
UPRT Certificate	Advanced UPRT mandatory since 20/12/2019	Advanced UPRT mandatory since 20/12/2019	Advanced UPRT mandatory since 20/12/2019	Advanced UPRT mandatory since 20/12/2019	Advanced UPRT mandatory since 20/12/2019	Advanced UPRT mandatory since 20/12/2019
Flight School Report	Mandatory	M	M	M	Mandatory	M
References	Not required	Mandatory	M	M	M	M
Vetting Procedure	Not required	Mandatory	M	M	M	Mandatory
Key Competencies	Not required	Essential Criteria to match	M	M	M	M
Age Limit	17yo to obtain PPL, 18 for CPL, 21 for ATPL	M	None	M	Not over 65	M

The database (of the ATPL exam) is of 19,000-20,000 questions. Memorizing those questions without a comprehensive understanding of the content is possible and poses a risk to the successful training of pilots according to Adonov. All interviewees confirmed that airline assessments are not too difficult and do not differ significantly from the syllabus of ATOs. Table 2 compares the ATO and Airline Minimum Requirements. The interviewees suggest that the difficulties seem to be in applying or even remembering the theory.

A very big issue seems to be the transfer from theory to practice, but when the exams only focus on rote-learning it is difficult to encourage cadets to gain a comprehensive understanding of concepts when it is a lot easier to just learn them by heart. The second reason - 'Communication skills' range from the level of English proficiency by the cadet to the actual way of communicating (tonality, clarity, etc.). This can be at improved by ATOs by possibly providing additional lessons for students, at least concerning Aviation Operational English on top of the typical modules or outsourcing that to competent language schools. Finally, core competencies are also important. Core competencies can be taught to some extent, but they are at the end of the day something people either have or do not [8].

The APS MCC system seems to cover almost all points from the main reasons mentioned above. Considering it has managed to improve initial approval figures up by 25% on the pass rates, it should be considered by ATOs as an addition to the syllabus [31]. This seems to benefit most parties since ATOs would not have to increase screening processes and pre-training, which could have resulted in a lower amount of students annually, but still, they would be able to guarantee higher quality cadets, who have a seemingly higher success rate for passing airline assessments.

Additionally, almost all interviewees believe that there is a significant correlation between the fees an ATO charges and the quality of training with the higher prices ATOs offer a better training. Interviewees Hornfeldt and Ryan suggest that low fees pose challenges to ATOs in securing quality instructors and aircraft, but attractive training material and facilities. The anonymous interviewee believes that price is less correlated to quality since price depends on the market's economic situation and a country in Eastern Europe with a living wage being a fraction of that of some western countries cannot be expected to charge the same fee with Western ATOs (approximately €120,000). The interviewees argue that between ATOs in the higher priced bracket the difference in quality is actually very little and that reputation and ATO-airline connections explain the small price differences.

According to interviews conducted with Adanov, Anonymous and Forrest, the top factors influencing the choice of the pilot academy for student-pilots are: a) Price, b) Location and c) Quality of training. Of course, there are exceptions to this rule where 'Quality' is actually the top deciding factor, but for the majority of cadets 'Price' is indeed the biggest element. This typically splits the price-sensitive students with those who seek reputation and best quality.

Those who are price-sensitive who seem to be the majority, and are self-sponsored, need to consider additional costs (e.g. relocation) according to interviewee Ryan and therefore their choices of ATOs are even more limited to those with no financial constraints. The socio-economic background of the potential pilots is posing restrictions for their access to quality training and many times attend 'cheaper, but of lower quality' ATOs. Due to this, ATOs that are of lower or barely-acceptable quality are still getting students to train with them and they have no incentives to improve the quality of service. Many times, they promote high employability rates capitalising in the strong industry trend –at least prior to COVID-19. However, the quality of graduating pilots is questionable.

If ATO minimum assessments for training standards and airline assessments supposedly do not differ significantly, then some of the 50% of pilots who fail should not be able to become pilots at all, or at least until they either redo parts of their training or improve certain skillsets. Yet, with unemployment of only 8% (Note this is all before COVID-19 became a global pandemic. Since then, numbers may differ greatly), it means that 42% of students, who fail, still manage to get jobs in other airlines. However, a presumption that must be made is that not all 50% of those pilots who fail are completely inadequate. Some of them are failing due to unfortunate circumstances on the day. Others could have still been properly trained, but simply did not 'make the cut' just barely and found work elsewhere while still being of very sound quality. As the anonymous interviewee said "...there are some people who simply may have performed poorly on the day of the assessment but may actually end up being very good pilots. There are also cadets who are indeed poorly trained and poorly prepared but of course it depends on what kind of additional training they would receive from the airline that then hires them".

Furthermore, there are other reasons for pilot unemployment too, aside from poor pilot qualification as it would be naïve to believe those assumptions account for all 42% and some of them even may go back and revise or retrain to pass again or may simply be taken in all the same to be further trained by the airlines. This latter method was in-depth discussed with Stanulov when looking into the Lufthansa Technik's approach to the global shortage of Technical Staff such as engineers. Stanulov said, "They dropped the standards for recruitment due to this high demand and simply decided to say "okay, we'll just train them more ourselves then". He suggests that this is a way for airlines to deal with the global pilot shortage too, encouraging them to engage in 'uptraining' even lower quality pilots to reach their own demand. All of this means that there are possibly airlines out there admitting pilots of lower standard than should be acceptable, and even if all 50% who fail aren't a concern, there still seems to be a considerable amount of them who most likely are worth raising worry. Especially considering that, multiple interviewees believe that the cadet flight logbooks are being forged with false hours. Kucarov believes that out of these 200 required hours, about 30% of the hours have not been flown by some pilots.

Kelly and Efthymiou stated that Pilot error has been attributed as the cause of many aviation accidents in the past [25]. From statistics available from Air Accident Investigation Units (AAIUs), in some of the major countries in Europe, the majority of accident reports are linked to 'smaller airlines' probably with less strict airline assessments for pilots. More accidents appeared to have occurred at least in 2019 by 'smaller airlines; but for a deeper understanding, an analysis into the causality of these accidents compared to the standards of pilot recruitment standards in the affected airlines would be more useful.

In a case from 2019, an accident report from the Safety Investigation Authority of Finland (SIAF) of flight MTL650P stated that "The airline had not completely complied with its own safety management system. Oversight authorities do not always detect the difference between the safety management that operators promise to follow and their real-world practices" [34]. This poses serious threats to the industry especially if this is found to be applicable to pilot recruitment by 'smaller airlines' where they aren't forced to comply strictly to the internal safety management system – the effects of which can become exponential if the pilots aren't of an acceptably high standard too as stated by interviewee Kucarov.

All of this leads back to some extent to the Interviewee Stanulov suggests that suggest only when a problem or an accident actually occurs do people go back to evaluate the training of these pilots and often it is far too late.

In an industry supposedly governed by safety, the lack of efficient and effective regulation imposed on ATOs to screen potential future pilots or train them to a more appropriate airline standard is a serious flaw. Furthermore, 'smaller airlines' should invest more heavily in pilot screening as well, though issues arise with this too as the predicted future pilot shortage does pressure these airlines to accept any candidates that apply more often than not. According to Stefanov some airlines' pilot recruitment process lacks thorough assessments and requires only the provision of documentation.

5. Conclusions & Recommendations

This paper established that the minimum standards set by regulatory bodies like EASA and ICAO for ATO's to achieve were of sufficiently high standards as they matched the minimum requirements for some of the top European airlines for cadet pilots. This meant that the reasoning behind the 50% failure rate of some cadet pilots of airline assessments in these very same airlines had to be something else. Some of the key reasons for failure were established to be Insufficient Technical Knowledge and Preparation; Poor Communication Skills; Poor Teamwork or Lack of Leadership. This paper determined that the main way of improving each of these aspects either relied on the students themselves or on the ATOs. Another possibility for the failure rates was do with poor regulation over how strictly the monitoring of students in ATOs was undertaken. Though minimum requirements have been set, implementation and constant application is never a guarantee, especially in places where profits may be prioritised. Moreover, this paper reviewed the possibility that the industry's safety standards on which it relies so heavily may be affected by inadequate training of pilots. This further highlights the necessity for strict airline assessments and their importance in keeping safety standards in the industry at an all-time high.

The responsibility for fixing the issue lies with ATOs and regulators. As stated by multiple interviewees, cooperation across the entire industry would be best for increasing safety, which in itself is no easy task. Increased regulation from ICAO and EASA is highly recommended pushing for stricter admittance and pre-screening protocols for new cadets to ATOs. EASA regulations and guidelines are not as strict for pilot training, as airline standards require for recruitments since they are the final entity in the chain responsible for the safety of people.

Further training in the form of the APS MCC system to be added by more ATOs is also necessary. Regular audits to ensure the existence, and boost the effectiveness, of their pilot assessments and recruitment processes in order to increase safety are also needed. The introduction of mandatory pre-screening at all ATO's as in an industry governed by safety values should be prioritised over the short-term business interests. Finally, the integration of the APS MCC system in the training syllabus of ATO's or making it a mandatory course for pilots to ensure they are capable of working in an airline environment to the airline standard can have a significant impact on effective training and success of pilots in assessments.

A further research on the factors that affect pilot performance in airline assessments as well as an empirical study on safety implications of pilots receiving certification from ATO's while being possibly unprepared is recommended. Moreover, pilot retention is another important area that remains under researched. The attraction, retention and promotion of female pilots should also be investigated. Finally, the impact of COVID-19 on pilots negotiating power and the business sustainability of ATOs need to be researched.

CRediT Author Statement

Lenard Mariyanov Adanov: Conceptualization, Investigation, Writing-Original Draft. **Andrew Macintyre**: Validation, Supervision. **Marina Efthymiou**: Validation, Writing-Review & Editing, Project administration

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International Journal of Aviation Science and Technology

Research Article

Relative Navigation in UAV Applications

Tuncay Yunus Erkec[1], Chingiz Hajiyev[2]

[1]Turkish National Defense University, Hezarfen Aeronautics and Space Technologies Institute, Yeşilyurt/Istanbul
tuncayyunus@gmail.com - 0000-0003-3357-0985

[2] Istanbul Technical University, Faculty of Aeronautics and Astronautics, Maslak/Istanbul 34469
cingiz@itu.edu.tr - 0000-0003-4115-341X

Abstract

This paper is committed to the relative navigation of Unmanned Aerial Vehicles (UAVs) flying in formation flight. The concept and methods of swarm UAVs technology and architecture have been explained. The relative state estimation models of unmanned aerial vehicles which are based on separate systems as Inertial Navigation Systems (INS)&Global Navigation Satellite System (GNSS), Laser&INS and Vision based techniques have been compared via various approaches. The sensors are used individually or integrated each other via sensor integration for solving relative navigation problems. The UAV relative navigation models are varied as stated in operation area, type of platform and environment. The aim of this article is to understand the correlation between relative navigation systems and potency of state estimation algorithms as well during formation flight of UAV.

Keywords

Relative Navigation
GPS
Kalman Filters
Unmanned Aerial Vehicles
Localization

Time Scale of Article

Received 6 October 2020
Revised until 1 December 2020
Accepted 5 December 2020
Online date 30 December 2020

1. Introduction

Unmanned aerial vehicles (UAVs) have contributed great many to military force air domain especially for surveillance, reconnaissance, attack and defense missions. Besides, UAVs applications in the private sector other than military purposes plays an important role with regard to weather, human reconnaissance, forestry and agriculture [1], and photogrammetry beyond the capabilities of a manned aerial vehicles due to their low cost development and zero risk of loss of human life. However, operating a single drone is possible only in a limited area, therefore it is not effective compared with multiple drones on a mission. A new concept has come out since the air operations referred to more than one drone and it has been called Multi-UAV operations. These operations do not call for a change of performance of each drone yet allows them to perform an assigned mission through mutual cooperation in order to benefit the accuracy and efficiency that allows diversity [2].

Swarm UAV concept is used commercial area such petroleum and pipeline checking applications [3, 4], cargo applications [5] and also movie sector. The development of new relative navigation methods of UAV has a financial aspect. Because of these factors, lots of academic studies are focused on UAV formation subject [6].

Relative navigation is employed in separate platforms for rendezvous, formation flight, stereo imaging. The relative navigation aims UAVs well as terrestrial or naval autonomous vehicles [7, 8]. In this study, methods of UAVs formation flight methods are focused and compared with each other.

Many researchers have been focused various types of UAV such fixed wing [9, 10], rotary wing [11, 12]. In this study, the relative navigation methods are defined general types of UAVs, not individually. For a desired swarm concept, there are two basic sections [13], one of them is navigating the formation and the other one is maintaining the formation. As a navigating aspect, the flight path of UAVs formation is determined for the

*: Corresponding Author Tuncay Yunus Erkeç, tuncayyunus@gmail.com, Tel: +90 531 6543003
DOI: 10.23890/IJAST.vm01is02.0202

leader to along track [14]. On the other hand, maintaining the UAV formation is related to, detecting, estimating and controlling the relative vector states of the UAV which are included in formation [15].

Some studies in the literature, Global Navigation Satellite System (GNSS) based relative navigation methods are seemed rightly and practiced excellently navigate to UAVs. Some research shows that, aerial refueling can be autonomously made by GPS based relative methods with UAVs via Relative Time Space Positioning Information (R-TSPI). Vertical Accuracy is degraded about 1cm and Horizontal accuracy is degraded about 3cm with 10 Hz GPS receiver via Extended Kalman filter (EKF) within GPS based relative navigation [16].

The relative approaches which are focused in this study, can be used for not only UAVs platforms but also space, terrestrial and naval platforms relative state vectors estimation. Besides the errors in the GPS measurement can be eliminated via filters and estimation algorithms via fault tolerant approaches. Positioning vectors can be predicted precisely regardless of GPS errors.

The main highlights of the paper can be summarized as follows. First, to focused the Guidance, Navigation and Control (GNC) architecture of UAV's formation. Control approach requirements are denoted. Seconds, target UAV's state vector tracking, estimation and control models are explained. Collision avoidance can be executed by the relative state vector estimation and control signals during formation performed as well. Algorithms which used for relative state vector estimations of UAVs in formation are highlighted. Third, the comparisons of relative models are defined with different aspects within one hand.

2. Control of Formation

A proper and careful understanding of the user needs for formation flying of UAV is key for an adequate design, implementation and operations of mission. The user requirements are driving each of these three activities :

- Design; Relative navigation sensors, actuators,
- Implementation; Number of ground stations,
- Operations; Level of onboard autonomy.

Understanding the user needs has a massive influence on the functionality and feasibility of the mission, as well on the cost and schedule of implementation. Unfortunately, this understanding is a very difficult task for most UAV missions, as the user and engineers typically have a completely different background with very limited insight into each other's domain and using different domain languages.

In this study, a key question to be answered is that of knowledge versus control. Two approaches may illustrate this question. A sensor web which is composed of swarm UAVs, once established in flight path, typically must either not be controlled at all, or only with moderate accuracy. To evaluate the payload data, collected by the web, it is usually sufficient to determine the positions of the UAV traditional-on- ground. Thus, a posteriori knowledge of the absolute and relative positions is fully sufficient. In this case, direct inter-UAV links or actuators may not be required by the mission.

On the other hand, a virtual instrument, distributed on two UAVs flying in formation, might need a constant distance between the UAVs. In this case, traditional knowledge is insufficient. Instead, a real-time knowledge of relative position is required which is the basis for a real-time control of the relative motion of the UAVs.

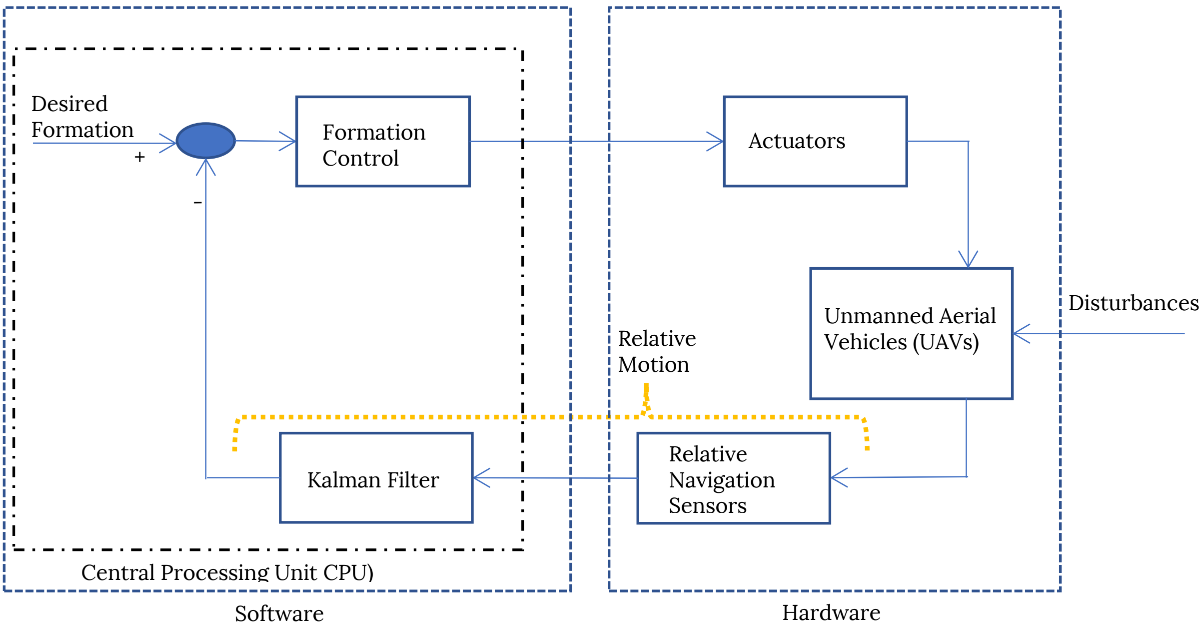

Fig. 1. Guidance, Control and Navigation (GNC) architecture for formation flying UAVs .

In such as case, a direct inter-UAVs link for cross-communication might be necessary along with precise relative navigation sensors and actuators. Guidance, Navigation and Control (GNC) (Fig.1), is vital sub-architecture for relative navigation of UAV missions [17].

As a result, there is no generally valid approach to establish the needs for controlling a formation. Knowledge versus control, availability versus control, availability versus latency, onboard autonomy versus ground automation, sensitivity versus robustness, are key trades to be performed when designing a formation flying mission.

3. Guidance Navigation and Control Concepts of UAV Formation

Establishing a formation of UAVs in flight path requires two phases: the acquisition of the formation and its maintenance, termed station-keeping. The acquisition phase depends, among others, on the concept of operations which describes e.g. how many platforms are applied to flight paths. Once formation is acquired, differential accelerations will slowly but gradually destroy the initial configuration. Depending on the specific users' needs for the mission, an active control of the relative geometry of the formation might thus be necessary.

Guidance, Navigation and Control (GNC) system must be installed which enables the platform-keeping of the formation during the desired time frame. Typically, a closed-loop control scheme is implemented onboard the UAVs (Fig.1). Guidance information for the formation may originate from ground operations or an autonomous process onboard the UAV. A formation control function determines actuator commands which trigger the activation of actuators. A potential misalignment of actuators and their non-ideal performance as well as external disturbances cause a deviation in the imposed velocity increment which, over time, originates in a slightly non-nominal relative position. The navigation sensors may not be able to sense the complete 6-dimensional state vectors. Thus a subsequent relative flight path determination function is necessary. As a consequence, the measured relative position will be different from the determined relative position.

Relative navigation relates with optimal state estimates about the position and velocity of one platform relative to the other one [18]. There are many traditional applications either as GNSS&INS integrated or ground based applications. However, these applications require extra link between components and sensor fusions sections [19]. Aside from these applications, the novel ones employ optics and image processing and detection & tracking models which are in line with enhancing image process and computational technologies. The aim of novel relative navigations models is to avoid from the complexity and increase the accuracy.

3.1. Sensors, Actuators, Software

Sensors for relative navigation and actuators for formation control are, together with a potential direct inter-UAV link, the key hardware components for formation flight (FF). In addition, operations of FF mission typically require excessive software, both onboard as well as on-ground. The requirements for all those key elements are driven by the specific user needs for the mission.

Here, one might either select existing absolute navigation sensors which might be used to differentiate the sensor data from several sensors (Fig.2) prior to or within flight path determination function to derive the relative flight path of FF UAVs. GPS receivers or conventional ground based tracking can be used for this purpose. Alternatively, dedicated FF navigation sensors may be used which are either based on radio-frequency (RF) measurements [20] or optical measurements [21]. Dedicated sensors are typically the most expensive option. However, especially RF sensors may be used in addition to distance sensing for inter-UAV communications which renders their use attractive for high-demand FF missions.

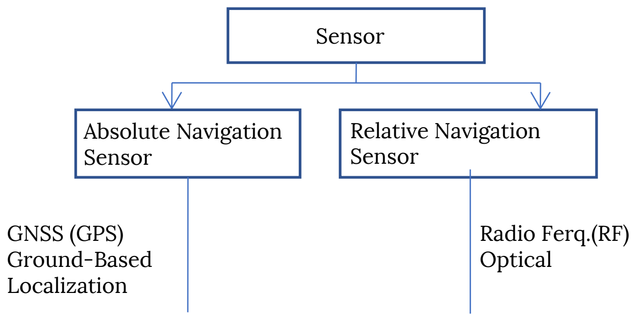

Fig. 2. Guidance, Control and Navigation (GNC) architecture for formation flying UAVs.

If a FF mission requires a dedicated acquisition phase and station keeping phase that needs to be controlled, actuators, which can actively change the relative motion of the formation, are typically required. Actuators may not only be used for formation acquisition and station-keeping, but may equally well be used for reconfiguration or resizing of the formation in the course of the mission. In addition, actuators may be used as well for a station-keeping of the absolute flight path of the formation. Actuators are most commonly thrusters and rotors which provide acceleration in a continuous or non-continuous mode. In selecting adequate thrusters for FF missions, key performance parameters are thrust level, or maximum duration of thrust. Design trades have to consider among others a potential distribution of maneuver capabilities over several UAVs in the formation and risk mitigation strategies for possible failure modes.

GNSS&INS Integration Based Relative Navigation Method of UAVs

Theoretical approaches are used for understanding of general relative navigation technology. Relative extended Kalman filter is used for integrating and upgrading heading and distance data acquired from GPS and Internal Navigation Systems (INS). This method calls for an additional link between the relative UAVs considering the transport navigation, speed, and attitude information. The GNNS&INS integration mathematical model has been shown Eq. (1-14).

GPS based relative navigation of UAVs with Relative Time Space Positioning Information (R-TSPI) accuracy is degraded to ± 1.0 m Position, ± 0.1 m/s velocity, ± 0.50 [16].

$$\Delta X_{ps}^{p} = X_{p}^{p} - X_{s}^{p} \tag{1}$$

X_p^p Primary's coordinates in primary plane,

X_s^p Secondary's coordinates in primary plane,

ΔX_{ps}^p Location difference between primary and secondary, these vectors can also be obtained from the primary/secondary strapdown inertial navigation solutions after transferring to the reference (eccentric) point. These vectors are transformed to the inertial frame, i-frame for using Eq.(1);

$$\Delta X_{ps}^{p} = R_{i}^{p}\,(X_{p}^{i} - X_{s}^{i}) \tag{2}$$

R_i^p Transformation matrix of i-frame to p-frame, where is the Primary attitude matrix which transforms from the i-frame to the p-frame. Eq. (2) represents the fundamental equation, from which the relative navigation equations are derived. This process is started by defining an interface frame, called a-frame, which is a completely arbitrary frame that rotates with respect to the i-frame. It should be noted that in this application everything is represented in the body frame of the primary, i.e., a=p. The relative position in the a-frame has coordinates in the i-frame given by:

$$(X_{p}^{i} - X_{s}^{i}) = R_{a}^{i}(X_{p}^{a} - X_{s}^{a}) \tag{3}$$

Taking one time derivative of Eq. (3) yields the relative velocity dynamic model;

$$(X_{p}^{i} - X_{s}^{i}) = R_{a}^{i} X_{ps}^{a} \tag{4}$$

a-lane is determined arbitrary as interface. It can change for i-frame. While solving navigation problem; All coordinates should be based on converted to primary object coordinate system.

$$\Delta \vec{\dot{X}}_{ps}^{i} = \dot{R}_{a}^{i}\Delta \vec{X}_{ps}^{a} + R_{a}^{i}\Delta \overrightarrow{\dot{X}_{ps}^{a}} \tag{5}$$

In Eq. (5), the time derivative of the rotation matrix can be written via Eq.(6).;

$$\dot{R}_{a}^{i} = R_{a}^{i}\Omega_{ia}^{a} \tag{6}$$

Where, Ω_{ia}^a denotes a skew-symmetric matrix, elements from $\omega_{ia}^a, \Omega_{ia}^a = [\omega_{ia}^a X]$. Thus, Eq. (5) can be expressed as;

$$\Delta \overrightarrow{\dot{X}_{PS}^{i}} = R_{a}^{i}\Omega_{ia}^{a}\Delta \overrightarrow{X_{PS}^{a}} + R_{a}^{i}\Delta \overrightarrow{\dot{X}_{PS}^{a}} \tag{7}$$

Taking the second time derivative of Eq. (7) to obtain acceleration dynamic model, the relative acceleration equation in the a-frame is established as:

$$\Delta \overrightarrow{\ddot{X}_{PS}^{a}} = R_{i}^{a}\Delta \overrightarrow{\ddot{X}_{PS}^{i}} - 2\Omega_{ia}^{a}\Delta \overrightarrow{\dot{X}_{PS}^{a}} - \left(\dot{\Omega}_{ia}^{a} + \Omega_{ia}^{a}\Omega_{ia}^{a}\right)\Delta \overrightarrow{X_{PS}^{a}} \tag{8}$$

In Eq. (8), the forcing term, $\Delta \overrightarrow{\ddot{X}_{PS}^{a}}$, can be expressed by the Primary/Secondary accelerations sensed by their accelerometers, $\overrightarrow{a_P^p}, \overrightarrow{a_S^s}$, as;

$$\Delta \overrightarrow{\ddot{X}_{PS}^{i}} = \overrightarrow{\ddot{X}_{P}^{i}} - \overrightarrow{\ddot{X}_{S}^{i}} = \overrightarrow{a_{S}^{i}} + \overrightarrow{g_{S}^{i}} - (\overrightarrow{a_{P}^{i}} + g_{P}^{i}) \tag{9}$$

where, $\overrightarrow{a_P^i}, \overrightarrow{a_S^i}$ are the specific forces, being also the quantity that is sensed by thePrimary/Secondary accelerometers, respectively; and $\overrightarrow{g_P^i}\left(\overrightarrow{X_P^i}\right), \overrightarrow{g_S^i}(\overrightarrow{X_S^i})$ are the accelerations due to the gravitational fields in the i-frame and it is a function of the position vector for the Primary and Secondary, respectively. Using Eq. (9), Eq. (8) is given by:

Eq. (10) represents that the relative navigation equation in the p-frame can be converted to a-frame. Because, integrations should be converted into a stable coordinate system. Desirable velocity is in e-frame which is parallel with p-frame and shown as, $\overrightarrow{V_{ps}^p}$

$$\Delta \overrightarrow{\ddot{X}_{PS}^{a}} = R_{P}^{a}\overrightarrow{a_{P}^{p}} - R_{S}^{a}\overrightarrow{a_{S}^{s}} + R_{S}^{a}\left(\overrightarrow{g_{P}^{e}} - \overrightarrow{g_{S}^{e}}\right) - 2\Omega_{ia}^{a}\Delta \overrightarrow{\dot{X}_{PS}^{a}} - (\dot{\Omega}_{ia}^{a} + \Omega_{ia}^{a}\Omega_{ia}^{a})\Delta \overrightarrow{X_{PS}^{a}} \tag{10}$$

$$\overrightarrow{V^{p}_{PS}} = R^{p}_{e}\Delta\overrightarrow{\dot{X}^{e}_{PS}} \quad (11)$$

The time-derivative of Eq. (11):

$$\frac{d}{dt}\overrightarrow{V^{p}_{PS}} = \dot{R}^{p}_{r}\Delta\overrightarrow{\dot{X}^{e}_{PS}} + R^{p}_{e}\Delta\overrightarrow{\ddot{X}^{e}_{PS}} \quad (12)$$

$\Delta\overrightarrow{\ddot{X}^{e}_{ps}}$ can be obtained from Eq. (9) by specialized $a \cong e$

$$\Delta\overrightarrow{\ddot{X}^{e}_{PS}} = R^{e}_{P}\overrightarrow{a^{p}_{P}} - R^{a}_{S}\overrightarrow{a^{s}_{S}} + \overrightarrow{g^{e}_{P}} - \overrightarrow{g^{e}_{S}} - 2\Omega^{e}_{ie}\Delta\overrightarrow{\dot{X}^{e}_{PS}} - \Omega^{e}_{ie}\Omega^{e}_{ie}\Delta\overrightarrow{X^{e}_{PS}} \quad (13)$$

By substituting Eq. (11) and Eq. (13) into Eq. (12), it yields the desire form of the relative navigation equation in the p-frame navigation equations.

Reference station is not stable, so that it can be called moving platform and it is main moving problem.

EBE (Epoch by Epoch) differential model; Vertical Accuracy is degraded about 1cm and Horizontal accuracy is degraded about 3 cm with 10 Hz GPS receiver via EKF. Real time relative pose estimations are recorded in primary UAV systems and second UAV is configured as a moving reference station [16].

Previous position information of UAV is subtracted from present position. Average values are least than 5 cm. However, link between UAVs is vital for maintaining the relative navigation. If the link or the GNSS information are exhausted, system faults will increase suddenly.

Measurement:

$$\vec{Y}(t_k) = [(\Delta\overrightarrow{X^{p}_{ps}})_{GPS} - (\Delta\vec{X})_{INS} \quad (14)$$

It is important that the distance between GPS receiver and IMU must be taken into account for calculation.

The GPS flight path prediction function (Fig.3) evaluates the flight path, provided by the position determination function, at 1 Hz rate and accounts for flight path maneuvers which might have been executed by the MAIN UAV in the past 30 seconds. It also outputs MAIN and TARGET UAV flight path states which are used by other onboard GNC functions as well as by the autonomous formation control function implementing the specific guidance and control algorithms described in the next sections.

Formation UAV concept has been successfully realized with GPS / INS integration. Besides, relative states sensitivity between UAVs depend on GPS signal continuity and strength. Signal interruption due to environmental factors can cause errors in GPS / INS relative navigation solutions. Low power condition in received GPS signals may cause interference to dominate the incoming GPS signal. Especially in cluster UAV applications in urban and mountainous areas, negative situations such as GPS signal failure can be encountered. In the literature, some studies and methods have been developed to solve the fault tolerant GPS-based formation flight problem in order to protect the formation architecture and avoid collision during GPS signal interruptions [57].

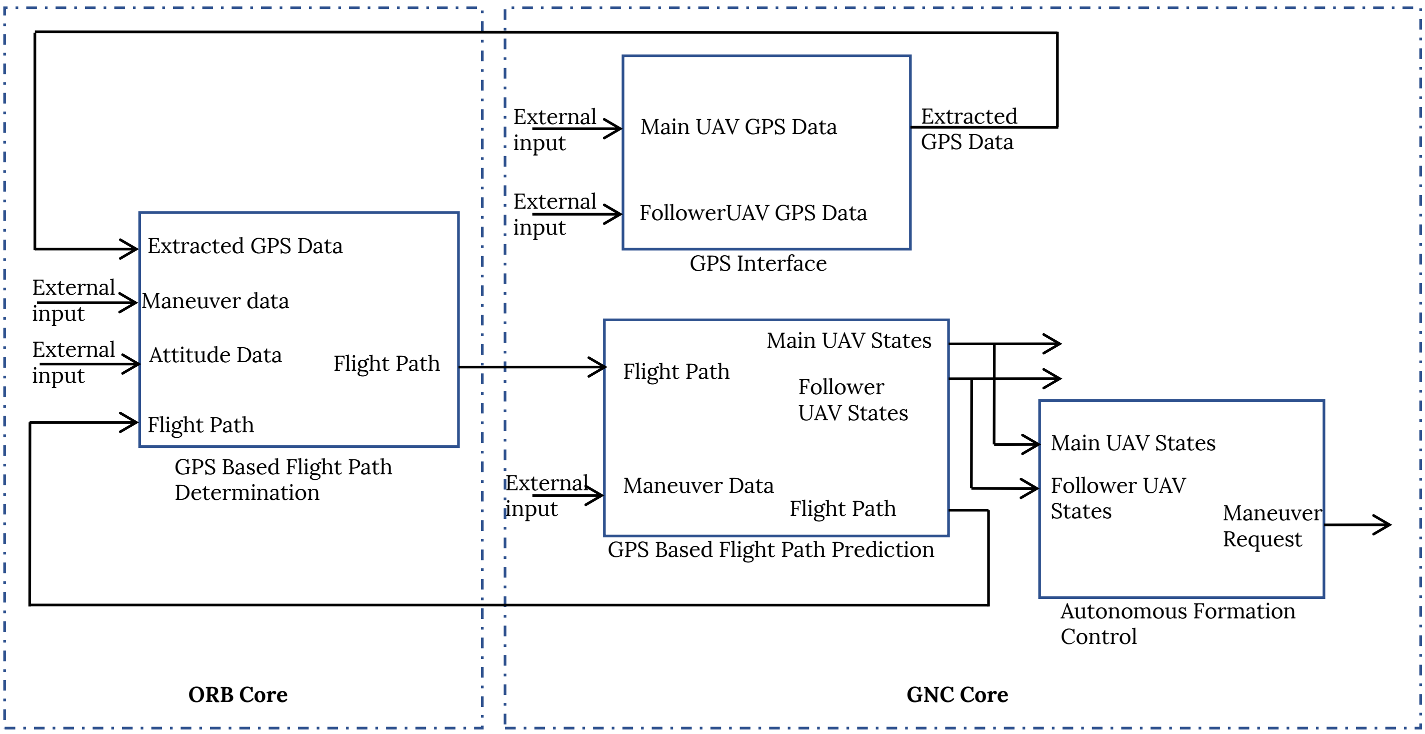

Fig. 3. Shematic software architecture for GPS based autonomous formation flying [22].

Using GPS signals, the best estimation of the relative state vectors between UAVs and minimization of errors with the 24-state Kalman filter is obtained (Figure 4).

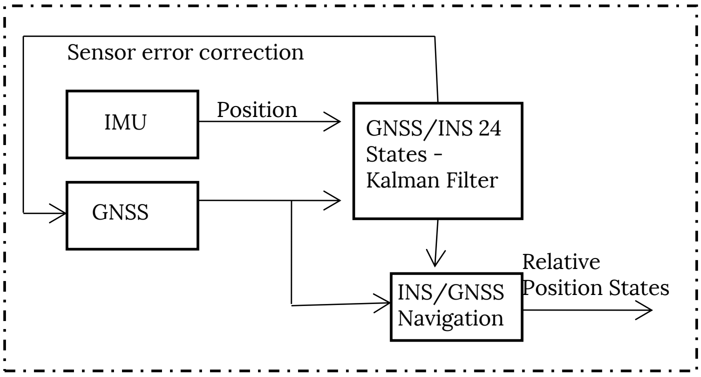

Fig.4. Integrated GNSS&INS relative navigation scheme of UAV formation [24].

INS and Vision Integration Based Relative Navigation Method of UAVs

Vision based sensors and INS fusion techniques, which are used for relative navigation, have been awaken some researchers interest since the developing technology via letting both INS and vision-based sensors getting smaller, lighter and cheaper. In some of these techniques, measurements are processed consecutive sequence rather than stack. Therefore, it is neither requires storing the full data set nor re-processing the existing states data when a new measurement becomes available [25].

Once single and noisy camera is used within INS&VISION based integration, INS itself can predict and detect position, orientation and velocity parameters via Inertial Measurement Unit (IMU). Through this prediction, sheer update of INS parameters (position, velocity and attitude) stands for the primary objective [26].

Owing to multi-sensor integration, relative UAV navigation is increasingly used in cluster UAV applications to achieve low cost and precise solutions. In recent years, more accuracy and precise solutions have been obtained thanks to the integration of visual based navigation sensors and GPS / INS based sensors. Movements and state vectors of other UAVs in the formation can be relatively detected with the CCD camera [27]. Stereo image processing is applied to determine the positions relative to each other within the UAV flight path navigation and formation, and the position information obtained from this processed image provides extra navigation information to GPS / INS based relative UAV navigation [28].

In the literature, studies on UAV formation architecture are increasing day by day with the use of GPS / INS / Visual based sensors together. High resolution CCD camera and complementary Laser Range Finder (LRF) can be used to make precise estimates of state vectors in 3 axes by detecting relative motion between UAVs (Figure 5).

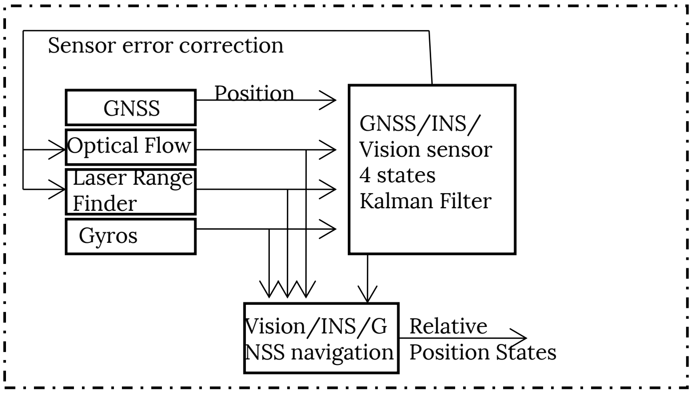

Fig.5. Integrated GNSS/INS/Vision based relative navigation scheme of UAV formation [24].

Vision Based Relative Navigation Method of UAVs

By and large, visual based navigation systems are applied so as to mitigate the dependency of external systems like GNSS during relative navigation missions [29].

The Vision Based Relative Navigation systems have been designed for near vicinity movements in UAV concept as rendezvous, docking and formation maneuvers. . Known position of the target in close range is specified by 2D, 3D or stereo imaging sensors (Fig.6). Relative position vector estimations and optimization of UAV, collision observations are calculated simultaneously. Calculated positions states are used for control systems which designated executing necessary corrections as if ΔV avoiding and corrective maneuvers within docking, formation flight, collision avoidance system [30]. However, Vision-based navigation has also been focused highly [31,32]. Terrain Aided Navigation System (TANS) typically useable of internal sensors and terrain database which prepared in advance [33,34].

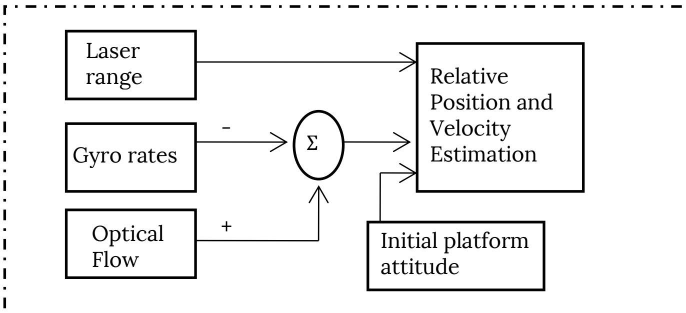

Fig.6. Vision based relative navigation flow chart [24].

Camera (Optic) has two direction errors. Vision based navigation state estimations are determined with LRF due to third direction respectively and denoted as LOF.

Hence, EKF is composed for estimating these errors with 4 states as shown as Eq. (15) [24].

$$X_{LOF} = [\delta\eta_b, \delta\eta_f, \delta\omega_{fx}, \delta_{fy}] \quad (15)$$

Where, $\delta\eta_b$ and $\delta\eta_f$ denote the LRF constant bias and measurement error. $\delta\omega_{fx}$ and $\delta\omega_{fy}$ camera (optic) flow measurement error x and y axis respectively.

The dynamic model of these four error states are used as zero mean Gaussian white noise.

The measurement vector z is determined by Eq. (16);

$$Z_{LOF}(t) = [V_{LOF}^H - V_{GPS}^H]^T = [H_{2\times4}]X_{LOF}(t) + V_{2\times1}(t) \quad (16)$$

Where, V_{LOF}^H and V_{GPS}^H are visual and GPS velocity measurements respectively.

UAV horizontal velocity in the body frame can be determined from the camera (optic), LRF and gyro angular rate have been determined by Eq. (17).

$$V_{bxy} = (\Omega_{xy} - \varphi_{xy}) \times r_{gz} \quad (17)$$

V_{bxy} are denoted translation velocities, Ω_{xy} camera (optical) measurement of angular rate, φ_{xy} are denoted rotation rates at two horizontal axis, r_{gz} is denoted height measurement which comes from LRF as noted Eq.(17).

The camera (optical) and LRF navigation error model is derived via Eq. (18);

$$V_{gxy} = [\Omega_{xy}(1 - \omega_{fxy}) - \varphi_{xy}](r_{gz} - \eta_b)(1 - \eta_f) + \varepsilon \quad (18)$$

ε is denoted bias due to sloping of Earth and errors EKF errors can be derived as Eq. (19);

$$\delta V_{gxy} = (r_{gz} - \eta_b)(1 - \eta_f)\delta\omega_{fxy} + [\Omega_{xy}(1 - w_{fxy}) - \varphi_{xy}] [(1 - \eta_f)\delta\eta_b + (r_{gz} - \eta_b)\delta\eta_f] \quad (19)$$

Hence, Eq. (20) represents the $H_{2\times4}$ matrix in Eq.(16);

$$H_{2\times4}\begin{bmatrix} [\Omega_x(1-\omega_{fx}) - \varphi_x](1-\eta_f) & [\Omega_y(1-\omega_{fy}) - \varphi_y](1-\eta_f) \\ [\Omega_x(1-\omega_{fx}) - \varphi_x](r_{gz}-\eta_b) & [\Omega_y(1-\omega_{fy}) - \varphi_y]\left(r_{gz}-\eta_b\right) \\ (r_{gz}-\eta_b)(1-\eta_f) & 0 \\ 0 & (r_{gz}-\eta_b)(1-\eta_f) \end{bmatrix} \quad (20)$$

The stochastic model of the EKF and the parameters should be designed according to the sensors' specifications.

Simultaneous Localization and Mapping (SLAM) Based Relative Navigation Method of UAVs

Simultaneous Localization And Mapping (SLAM) algorithm can be used to navigate UAVs in an unpredictable environment [35]. Since the onboard vision sensors detect landmarks on the other platforms and environment for relative navigation of UAVs. The SLAM estimates the platform position vectors with successive edge detection and observations [36,32].

Odometers, radar, GPS and several types of range finders such as sonar, laser and infrared supported sensors are commonly employed in SLAM techniques [37, 38]. BOSLAM (term Monocular SLAM is also used) as a fine solution to the SLAM problem is so helpful for supplying relative measurements. There have been a series of tremendous enhancements for BOSLAM over last year's [39-42].

The SLAM techniques are practical for indoor and/or outdoor environments and build up enormous splash Guidance, Navigation and Control (GNC) research field. In this day and age, vehicles are able to reach out to next flight through way-point and hold their exact position by using only visual data provided by the SLAM framework for marking the target of UAV missions. Some principal topics are robustness of solutions to the loss of the properties in the video images, being late in the communication processes, ways of eliminating the slow drift in behavior could have far more importance for long flights, succession UAV's environments without any external support [26].

Light Amplification by Stimulated Emission of Radiation (LASER)/Light Detection and Ranging (LIDAR) Based Relative Navigation Method of UAV

Laser systems are used for different kind of applications within Space and UAV as if Laser Range Finders (LRF) and Laser Target Designators (LTD), Laser Radars (Light Detection and Ranging-LIDAR), Laser Communication Systems (LCS) and Directed Energy Weapons (DEW). Besides, relative navigation, docking, 3D stereo mapping, remote sensing, detection, collision warning and obstacle avoidance are used with Laser/Lidar sensors frequently [43, 24].

Laser/Lidar based systems are used for different functions with different measurement techniques (Table 1).

Laser/Lidar systems can be used individually besides they are integrated into other systems (Fig.7) via sensor fusion due to increasing accuracy of relative state estimations and they are back up for laser sensors limitations due to atmosphere affects as if fog and clouds.

Table 1. Laser systems Functions and Measurement Techniques [44]

Functions	**Measurements**
Tracking, Sensing, Imaging	Amplitude (Reflectance)
Moving Target Indication (MTI)	Range (Delay)
Machine Vision	Velocity (Doppler Shift or Differential Range)
Velocimetry	Angular Position
Target Detection, Identification	Vibration Level

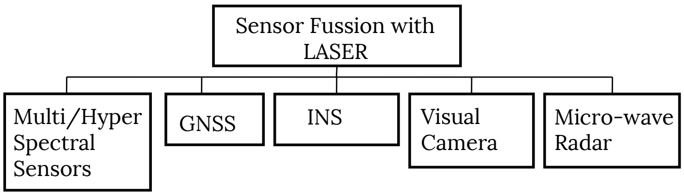

Fig. 7. Sensor Integration of UAVs formation concept [44].

Most laser systems are active devices that operate in a similar way to electromagnetic waves radars but at much higher frequencies (Table 2) [19].

Table 2. Wavelengths of some laser types [44].

Types of Laser	Wavelength
CO2	9.2-11.2 µm
Er:YAG	2 µm
Nd:YAG	1.06 µm
GaAIAs	0.8-0.904 µm
HeHe	0.63 µm
Frequency DuobledNd:YAG	0.53 µm

The useful effects of airborne laser systems including the smaller component and accurate angular resolution have been resulted in several UAV applications [24]. However, laser sensors are so vulnerable to dust, fog, and cloud of the atmosphere that makes these sensors far more limited within close ranges than microwave systems. Hence, analyzing the performance of laser sensors and systems in various weather and environmental conditions are substantial. What is more, specified airborne laser safety is considered as an important criterion due to the fact that multiple systems currently used within the near infrared create an enormous risk for the naked human eye. At this view, laser-based technologies are not considered as green methods, yet these technologies can use several platforms thanks to the locating accurate position and angular measurement abilities. Nonetheless, power consumption and weight always becomes a challenging issue for UAVs, therefore cost-effective Laser/Lidar sensors have been tried to be invented over last decades [44].

The microwave radar range equation is applied to laser systems and the power received by the detector P_R is given by Eq. (21);

$$P_R = \frac{P_T G_T}{4\pi R^2} \frac{\sigma}{4\pi R^2} \frac{\pi D^2}{4} \tau_{atm} \tau_{sys} \quad (21)$$

Where, P_T is the transmitter power, G_T is the transmitter antenna gain, R is the range (m), D is the aperture diameter (m), τ_{atm} is the atmospheric transmittance and τ_{sys} is the system transmission factor. With laser systems, the transmitter antenna gain is substituted by the aperture gain, expressed by the ratio of the steradian solid angle of the transmitter beam width a^2 to that of the solid angle of a sphere which is noted Eq. (22).

$$G_T = \frac{4\pi}{a^2} \quad (22)$$

Relative Navigation Algorithms for UAVs

In this part, as mentioned above, using algorithms for control section of UAVs which are used for not only sensor fusion but also detect and estimate the target UAV motions, UAV's movements such as Kalman, particle filters. Estimation of States, which are converted from non-linear movement characterize to linear within a divided time periods are predicted. On the other hand, math and physical models of system must be well defined.

For linear randomize systems, Kalman filters are well-known for their popular state estimation, prediction, optimization techniques [45]. One interesting issue as to Kalman filters is that they call for an precise system model and accurate noise statistics data. By virtue of these restrictions, applications can be hardly implemented in real life. Deficiency of information causes enormous estimation errors as well as filter accuracy.

Some of related works on monocular SLAM predicated on extra sensors [46], Extended Kalman Filter (EKF) is improved for velocity position and behavior estimation of a UAV with using low-cost sensors which are created by a sensor-fusion algorithm. Especially, an IMU and an optical-flow sensors which include a laser module and an extra gyroscope can be used [29]. In fusing inertial sensors with camera in an iterated EKF is suggested.

The extended Kalman filter (EKF) has been the most comprehensively used application for nonlinear filtering problems so far. However, it works well only in the linear regime in which the linear approximation of the nonlinear dynamic system and it is compatible only when the observation model is valid [47]. Recently, a cubature Kalman filter (CKF) [48] based on the third-degree spherical-radial cubature rule has been proposed and employed with various applications, such as positioning [49], sensor data fusion [50] and attitude estimation [51]. The cubature rule is derivative-free and the number of the scaled cubature points is linearly with the state-vector dimension, which makes the CKF could be applied in high-dimensional nonlinear filtering problems. Compared with the EKF, the CKF has better convergence characteristics and greater accuracy for nonlinear systems [48]. According to the academic simulation outcomes, the proposed filter provides far more accurate estimates for relative attitude and position than the extended Kalman filter [47].

Some researchers also use different algorithm systems which are Monte Carlo Simulation Method [52, 53], Lyapunov Method [54, 18], etc. or novel versions of Kalman filters as if Cubature Kalman filters [47], Adaptive Fading Kalman Filters (AFKF) [55, 56], Federal Kalman Filters, for increasing accuracy of linearization, estimation, optimization of states within not only flying vehicles but also all movement vehicles for autonomous control, docking, relative navigation aims [57]. Multiple hypotheses filters, filtering techniques, Sum of Gaussians [58], Particle Filters [59] and extensively various estimation and filtering techniques [60] have been studied by some authors.

Some of the most eligible notes of these works still are based on the well-known Extended Kalman filter [61,62]. Kalman filters have proven themselves not only in theory but also in practical usage of real systems. However, state estimation of non-linear stochastic systems suffering low performance and repellency along with the noise distribution in the Unscented Kalman Filter (UKF) are incompatible to a real system which is broadly used by UKF [63].

3.2. Impact on Mission Architecture and UAV Bus

Designing, implementing and operating a successful FF mission needs to consider the FF mission needs to consider the FF aspects on all elements of the mission architecture.

1. Subject,
2. Flight path and constellation, (design of relative formation geometry)
3. Payload, (Camera, military payload)
4. Platform, (UAV body types)
5. Ground element,
6. Mission operations,
7. Command, Control and Communications architecture (inter-UAV link, relay options)

From an engineering point-of-view, the impact of FF on the UAV, payload and bus are most interesting. Of these two aspects, the payload is critically driven by the user needs. For the UAV bus, FF does not only affect the navigation sensors and control actuators as described above, but has an impact on various other subsystems.

- Attitude Control System (ACS) (relative pointing for payload operations or inter-UAV link),
- Guidance, Navigation, Control (GNC)(additional relative GNC functions),
- Propulsion (Prop) (FF control and flight path control),
- Structures and mechanisms,
- Electrical Power System (EPS),
- Thermal Control Systems (TCS),
- On board Data Handling System (OBDH),
- Telemetry, Tracking and Command (TTC) (additional bandwidth for payload and FF operations)

4. Results and Discussion

For autonomous UAV systems, complexity reveals itself in different ways;

1. Complexity of environment,
2. Complexity of task to be perform,
3. Complexity of Co-operation between multiple autonomous systems.

The environment encountered by autonomous system varies in a large scale. Generally, UAVs operate in relatively simple and forgiving environments. On the contrary to the ground plane, a UAV's environments are utterly obstacle free. Although a world representation is not required for UAV's environment, there are slight environmental conditions which create other forms of complexity. This complexity can be separated into two groups;

Firstly, atmospheric effects such as turbulence, shear and vortices influence the vehicle's motion dramatically. These effects may have a considerable influence on the vehicles linear and angular motion, and they are potentially catastrophic in terms of accident.

Secondly, other contributors are to accounted as complexity of boom motion during aerial refueling, deck and optical system motions during carrier landing.

Ascribed to the complexity associated with environments, autonomous vehicles have to sense to a certain degree in order to comprehend their environment. The process of representing and understanding the Earth can be deemed from many aspects. For instance, a stationary sensor has the ability to create an Earth representation, yet its inability to move regards that representation has a constricted internal use. A sensor located on a man plotted vehicle can create an Earth representation since the humans are able to enhance situational awareness by interpreting and understanding the Earth. Tele-operated vehicles call for a human guidance in the loop in which there is a heavy dependence upon human for input and guidance. Therefore, the tele-operated vehicle has limited requirements for Earth representations [64].

Complexity, automation and autonomy appear as a whole single entity as well as multiple platforms. In this regard, each system may be preferable depending on the mission requirements. A problem expected to well resolved by single asset solution could be identified. Below there is a bunch of characteristics which shown in Table 3 as an example to this identification.

Table 3. Comparison of single and multiple UAV concepts [64].

Single Platform	Multiple Platforms
Hard to separate into pieces, Highly interdependent system dynamics,	Easy to separate into pieces., Dynamics are loosely coupled, Time-scale separation is apparent,
Physical dispersion adds little benefit, Simultaneous actions add little, Sequential tasking is adequate/optimal,	Physical dispersion can be used to great effect, Simultaneous tasking has great utility, Sequential tasking is inadequate,
Information transfer is costly/inadequate, Threats make communication undesirable, Geographic separation makes communication difficult, Terrain/environment make communication difficult.	Information transfer is not costly, A global information state can be maintained, Local information is adequate, Lags and latency are acceptance.

All these with the caveat of the complexity problems are so overwhelming that separation remains the sole realistic option available. The benefits of having multiple assets add degrees of freedom to the problem resolution. However, this flexibility comes with a cost which could be regarded as an additional complexity imposed in the form of limitations. A target must be validated before an attack and battle damage has to be assessed before the attack. For this reason, the meaning of "complexity and automation" for multi-platform systems probably imply different concepts from those associated with single platform systems.

Other key factors that make a multi-asset solution aside from a single-asset solution are:

1. Problem division,
2. Information availability.

The former includes actions/items such as order of precedence (kill chain), coupling of tasks, performance and computations. The latter deals primarily with communication, centralization of processing, correlation of targets and moving platforms [55].

In the formation architecture, the joint movement between UAVs and the behavior characteristics of a single UAV are preserved during the decision process. The architecture was established on a single center control. Meanwhile, there must be a communication between all UAVs via the inter-UAV link. Task features, cross-platform communication, and uncertainty management have an impact on the interoperability level. This situation creates a complex structure. There is no collaboration process that can take all inputs and variables into account. However, by dividing it into sections, the solution is tried to be simpler, although the totality is lost. Although this solution is not the best solution for collaboration and task, it is a solid and acceptable solution.

Cluster UAV control and optimal selection problem can be separated functionally by numerical and mathematical models. In the UAV formation concept, subset and task formation can be done in conjunction with theoretical methods [65], discretization approaches [66] and relative profit-loss techniques [67]. Subset optimization problem can be examined under many subtitles. While determining and simplifying the main mission goal, the task and timing of each platform forming the formation should be determined. Each UAV sends its mission requirements and information to the central decision department. Algorithms for multitasking, heuristic search methods, discretization and limiting [68], linear programming approach [68] include iterative network flow. The complexities of multitasking can be absorbed by task integration.

4.1. Comparison

Traditional techniques such as GNSS, INS based on integration are used in UAV's as well as other platforms. Also, these techniques are both compatible with commercial planes, cars, ships and not energy limited opposes to small UAVs. However, a lot of studies are focused on techniques for these platforms not only fixed wing but also rotary wing [69,70] due to autonomous control, especially Guidance, Navigation and Control (GNC).

Traditional methods like GNSS based relative navigation approaches have been limited by coverage area which served by GPS, GLONASS, GALİLEO satellites, on the other hand, it gives more accurate and continuous location information and also cost effective for designing small UAV's power systems. Using GNSS and ground stations for relative navigation applications are expensive. It seems like a challenge for using laser sensors within UAVs due to limited power budget. However, it can be integrated other methods like INS, laser, vision sensors.

Laser/Lidar based sensors are vulnerable to dust, fog and clouds according to wavelengths. Yet, these sensors are very accurate for detecting. Visual and GNSS based

UAVs relative navigation methods comparison is shown in Table 4.

Table 4. Comparison of Visual and GNSS based relative navigation of UAVs [19].

	Visual	GNSS
1.	Green Method (no energy dissipation required).	It is based on electromagnetic wave energy.
2.	Wide sensor requirements viewing range.	UAV and GNSS coverage is required.
3.	Short distance solutions.	Relatively long-distance solutions.
4.	The extra inter-UAVs link is not required, provided autonomous solutions.	Link between UAVs is required.
5.	The relative motion sensitivity depends on the sensor sensitivity.	The relative motion depends on the GNSS information sensitivity.

The sensor integration is used for overcoming these complexity and navigation issues in formation concepts. The sensors vary according to accuracy and data rate which used for measurement from source. The sensor properties are shown in Table 5. Kalman filters are used for integrating sensor. Inter-UAV link should be established for sharing navigation data in formation.

Table 5. Example of sensor properties for UAV navigation [24].

Sensors	Data Rate	Accuracy
INS (IMU7000CB)	50 Hz	Gyro: Scale <2% Bias<20deg/hr Accelerometer: Scale<1%
GPS (Novatel RTK)	20 Hz	2 cm 0.05m/s
Optical (CCD Camera)	50 Hz	Scale<2%
LRF	25Hz	Scale error<1% Offset<10cm

5. Conclusion

In this Study, relative navigation methods which are used for UAVs are focused on different approaches. The vision based relative navigation methods have been attracted attention by some researchers during last decades thanks to their remarkable advantages. However, traditional GNSS and INS based methods have proven themselves at online platforms within several environments even though they have coverage limitations.

Algorithm types which used for estimate states of relative parameters are chosen according to analyzing the nonlinear motion. Kalman filters such as extended, unscented, cubature algorithm models need input data which come from measurement and models. However, they are run by online system simulations successfully.

Formation flight concept on UAVs is focused in this study and compared between single and multiple platforms usage for UAV in the area of interest. Besides, Vision based and GNSS based relative states estimation approaches are compared each other.

The methods of UAVs are relative navigation state estimates are chosen according to platform, mission and accuracy requirements. The sensor and algorithms development will be affected to selecting relative approaches on UAVs. The final point of relative method selections is fully independent, autonomous and effective due to mission requirements.

In conclusion, the article highlights the relative navigation methods of UAVs and the impact factor of formation architecture from different perspectives. The complexity and comparison between relative methods are examined in terms of motion detection sensor properties. With this study, it is aimed to be a guide in the selection of relative navigation methods and predictions of their complexities in future formation unmanned aerial vehicles missions, taking into account the environment, mission and platform characteristics.

Abbreviations

UAVs	:	Unmanned Aerial Vehicles
GNSS	:	Global Navigation Satellite System
INS	:	Inertial Navigation Systems
EKF	:	Extended Kalman Filter
GPS	:	Global Positioning System
SLAM	:	Simultaneous Localization and Mapping
R-TSPI	:	Relative Time Space Positioning Information
EKF	:	Extented Kalman Filter
GNC	:	Guidance, Navigation and Control
FF	:	Formation Flight
RF	:	Radio Frequency
EBE	:	Epoch by Epoch
IMU	:	Inertial Measurement Unit
LRF	:	Laser Range Finder
LTD	:	Laser Target Designators
LIDAR	:	Light Detection and Ranging
MTI	:	Moving Target Indication
CFK	:	Cubature Kalman Filter
AFKF	:	Adaptive Fading Kalman Filter
ACS	:	Attitude Control System
EPS	:	Electrical Power System
TCS	:	Thermal Control System
OBDH	:	On Board Data Handling System
TTC	:	Telemetry, Trackiing and Command
TANS	:	Terrain Aided Navigation System

CRediT Author Statement

Tuncay Yunus Erkec: Writing-Original draft preparation, Writing-Reviewing and Editing, Software, Investigation, Data Curation. **Chingiz Hajiyev**: Supervision, Conceptualization, Validation, Project administration, Resources, Funding acquisition

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International Journal of Aviation Science and Technology

Research Article

Design and Analysis of Combustion Chamber for HAN Based Mono Propulsion System Thruster for Spacecraft Application

Naresh D C[1], Rudresh M[2]*, Debadatta Mishra[3]

[1] *Assist. Prof., Department of Aeronautical Engineering, Dayananda Sagar College of Engineering, Karnataka, India.*
naresh-ae@dayanandasagar.edu - 0000-0002-6903-9777

[2] *Assist. Prof., Department of Aeronautical Engineering, Dayananda Sagar College of Engineering, Karnataka, India.*
rudresh-ae@dayanandasagar.edu - 0000-0003-3440-8488

[3] *Liquid Propulsion System Centre, ISRO, Karnataka, India.*
dcnaresh4@gmail.com

Abstract

This paper presents a preliminary dimensional study of combustion chamber using Hydroxyl Ammonium Nitrate (HAN) propellants for spacecraft application. The combustion chamber consists of two parts namely thrust chamber and Convergent-Divergent (C-D) nozzle. The design for combustion chamber is very much important because the chemical energy in the propellant released within this closed volume i.e., thrust chamber and gets expanded through the C-D nozzle part. So the chamber must be designed to provide a necessary space for the propellants to react and release maximum available energy and also it should prevent the loss of energy in the form of heat. The C-D nozzle should be optimally designed to allow the maximum conversion of enthalpy into kinetic energy. So, the thrust chamber and C-D nozzle are designed in an optimum size for releasing the heat to convert maximum available heat energy from the combustion of HAN propellant into exhaust velocity for HAN based monopropellant thruster. In this work the combustion chamber i.e. thrust chamber and C-D nozzle are designed at 16 bar pressure to generate a thrust of 11 N. CFD analysis is done to show the pressure and temperature variation in the combustion chamber modeled for 11 N thrust and chamber pressure of 16 bar for spacecraft application. From the analysis result it is found that monopropellant engine with the propellant combination of HAN+ Methanol+ Ammonium Nitrate + Water is suitable for design of Attitude & Orbit Control System (AOCS) thrusters.

Keywords

Hydroxyl Ammonium Nitrate
Computational Fluid Dynamics
Attitude and Orbit Control System
Mono Propellant Thrusters
Combustion

Time Scale of Article

Received 29 September 2020
Revised until 6 November 2020
Accepted 27 November 2020
Online date 30 December 2020

1. Introduction

The development of green propellants is the main focused topics in the space organizations across the world. Indian space research organization is focused more on development of green mono propellant such as HAN as an energy source for spacecraft AOCS thrusters. Combustion of the monopropellants occurs by decomposition under the preheated catalytic environment. So the design of the combustion chamber for mono propellant combustion should provide the housing for catalyst loading as well as the space for the chemical reactions. The combustion chamber is the volume in which the chemical energy in the propellant gets converted in to heat energy. The energy stored in the reaction products should not get loss in any form. So the design of combustion chamber should be optimum in size within it should provide necessary space for the reaction. Since these chambers are used for the small and medium range spacecrafts its size should be optimum because the space available for inserting these

*: Corresponding Author Rudresh M, rudresh-ae@dayanandasagar.edu Tel: +919663002589
DOI: 10.23890/IJAST.vm01is02.0203

thrusters is small. Here in this present paper, since we are using the HAN based green monopropellants the iridium catalyst is used for the decomposition with preheated in range of 390-450K [1, 2]. Since from some literatures suggested the stay time of the HAN based propellants are around 1.2 to 35 milliseconds we considered this value and calculated the characteristic length of the combustion chamber. A transition from hydrazine to less environmentally hazardous monopropellants with higher specific characteristics is considered to be perspective for thermos-catalytic thrusters which are used for spacecraft attitude control and station keeping. Such propellants are commonly named as "green propellants" [3].

Hatem Houhou et. Al. [4] carried out dimensional study on combustion chamber using LOX/LCH4 as propellants. Their results offered guidelines for the design of important parts of combustion chamber which is most essential in design of rocket engine.

Here in this paper we attempted the design and analysis of combustion chamber at 16 bar pressure with C-D nozzle assembly for 11N AOCS thruster using HAN as a propellant. The combustion parameters are simulated in NASA CEA Run and 2D CFD analysis is done in Ansys Workbench. The theoretical and CFD values are compared to arrive at the conclusion.

2. Design of Thrust Chamber

The mono propellant combination of HAN and Methanol has high specific impulse compared to other mono propellant combinations have been used in AOCS thrusters [5]. The thermal analysis is a major issue at the channel exit. Those parameters are important for the design of injectors and of the coolant pump [6] is also considered. The prediction of peak heat-flux from the combustion gases to the engine wall is necessary to ensure the structural integrity of the combustion chamber. The need for thermal analysis is essentially important to extend the thruster life by effective and efficient cooling system. Moreover, the analysis of the cooling channel flow is essential to predict not only the efficiency of the coolant, but also the coolant temperature and pressure. The design of thrust chamber consists of many parameters and detail calculations, using basic geometric parameters are adequate to understand the regenerative cooling effect of the system [7]. For the built-up of gas-dynamic profile of the combustion chamber, it is necessary to give some input data to the system such as thrust, chamber pressure, ambient pressure and propellant components. Some of these parameters are listed below in the table.

Table 1. Mono Propellant Requirements [2]

THRUST(F)	11 N
Propellant	HAN+ Methanol+ AN + H_2O
Camber Pressure(P_O)	16 bar
Ambient Pressure	For Space It Is Considered To Be Zero.

Chamber pressure is very important in the designing of rocket engine [6]. The thrust chamber performance increases with increase in chamber pressure and also higher chamber pressure reduces the performance losses due to kinetics. Thrust chamber size and weight decreases as the chamber pressure increases. Higher chamber pressure provides higher nozzle expansion ratio, which in turn reduces the chamber and nozzle envelope for a fixed thrust. As area ratio (AR) increases, the specific impulse increases, due to higher expansion of hot gas which generates higher velocity at nozzle exit. But AR is primarily selected based on the application of engine [3].

2.1. Calculation of Chamber Throat Diameter

The performance parameters are obtained through NASA-CEA code for the given input condition of the engine. Those values are listed in the following table.

Table 2. Performance parameters from CEA run

Parameters	Values
Characteristic velocity (C^*)	1419 m/s
Specific impulse I_{sp}	262 s
Thrust coefficient, C_f	1.81
Molecular weight	22.91

Total mass flow rate can be calculated from the following equation [1]

$$F = I_{sp} * g * \dot{m}_{total} \quad (1)$$

$$\dot{m}_{total} = \frac{F}{I_{sp} * g}$$

$$\dot{m}_{total} = \frac{11}{262 * 9.81}$$

$$\boldsymbol{\dot{m}_{total} = 4.27 \text{ Grams / second}}$$

$$C^* = \frac{A_t * P_0}{\dot{m}_{total}} \quad (2)$$

Area of the throat: $A_t = \dfrac{C^* * \dot{m}_{total}}{P_0}$

$$A_t = \frac{1419 * 4.27E - 3}{16E + 5}$$

$$\boldsymbol{A_t = 3.78E - 6 \ \text{m}^2}$$

Diameter of the throat: $D_t = 2.19\ mm$

Radius of the throat: $R_t = 1.095\ mm$

The chamber volume is the function of mass flow rate of the propellants and their average density and of the stay time needed for efficient combustion [1].

Combustion chamber volume (Vc): $V_c = \dot{W}_{tc} * V * t_s$

Characteristic length (L^*):It is defined as length that a chamber of the same volume would have if it were a straight tube and had no converging nozzle section.

Characteristic length for the above propellant composition is assumed to be same as Hydrazine because the HAN and Hydrazine belongs to the hydroxylamine salt group.

$L^* = 875\ mm$ [1]

$V_{total} = L^* * A_t$

$V_{total} = 875 * 3.78E-6\ \text{m}^3$

$V_{total} = 3307.5\ mm^3$

$V_{total} = V_c + V_{convergent}$

While designing the combustion chamber, proper value of L* is to be considered because an increase in L* beyond a certain limit results in decrease in overall engine system performance. In case of operating monopropellant low thrust engines the contraction ratio varies in the range from 1.58 to 5. Design of very high contraction area ratios (> 5) have difficult in maintaining stable boundary layer, adjacent to the throat [1].

2.2 Selection of Chamber Internal Profile

The configuration of the combustion chamber is cylindrical which provides sufficient surface area for cooling. For this engine configuration, semi convergent angle of 15 degrees has been selected, favoring a lower heat flux and thereby maximizing the life of the chamber. For current engine configuration the nozzle throat has the contour of circular arc with a radius of R ranging from 0.5 to 1.5 times the radius of the throat. The half angle of the nozzle convergent portion is 15.

Convergent portion length

$$\epsilon_{convergent} = \frac{A_{inlet}}{A_t} \qquad (3)$$

$$L_{nozzle} = \frac{R_t(\sqrt{\epsilon_{convergent}}-1)+R(see\theta-1)}{tan\theta} \qquad (4)$$

Where $\theta = half\ angle\ of\ the\ covergent\ portio$

The half angle of the convergent portion is assumed to be 15 to 20 degree.

R= radius of curvature at the throat it is assumed to be 0.5 to 1.5 times the R_t

Here assumed as

$R = 1.5\ R_t = 1.5 * 1.095 = 1.6425$ mm

For $\theta = 15^0$

$$L_{nozzle} = \frac{1.095(\sqrt{5}-1)+1.6425(see15-1)}{tan15}$$

$L_{nozzle} = 5.26\ mm$

$$\epsilon_{convergent} = \frac{A_{inlet}}{A_t}$$

Area of the inlet: $A_{inlet} = 5 * A_t$

$D_{inlet} = \sqrt{5} * 2.19$

Diameter of the inlet: $D_{inlet} = 4.89$ mm

Radius of the inlet: $R_e = 2.445$ mm

For $\theta = 15^0$

$$V_{convergent} = \frac{\pi}{3} * 5.26\,(1.095^2 + 2.445^2 + 1.095 * 1.095\,)$$

$V_{convergent} = 54.25\ mm^3$

Volume of the Chamber V_c

$V_{total} = V_c + V_{convergent}$

$V_c = V_{total} - V_{convergent}$

The cross sectional area of the combustion chamber is assumed to be equal to the inlet cross sectional area of the nozzle

Therefore $A_{inlet} = A_{chamber} = 18.77\ mm^2$

$V_c = A_{chamber} * L_{chamber}$

For $\theta = 15^0$

$V_c = 3307.5 - 54.25$

$V_c = 3253.25\ mm3$

$V_c = A_{chamber} * L_{chamber}$

$$L_{chamber} = \frac{V_c}{A_{chamber}}$$

$$L_{chamber} = \frac{3253.25}{18.77}$$

$L_{chamber} = 173\ mm$

Divergent portion length

$$L_{nozzle} = \frac{R_t(\sqrt{\epsilon}-1)+R(see\alpha-1)}{tan\alpha} \qquad (5)$$

Where α = half angle of the divergent portion

The half angle of the divergent portion is assumed to be 15 to 20 degree.

R= radius of curvature at the throat it is assumed to be 0.5 to 1.5 times the R_t

Here assumed as

$R = 1.5\, R_t = 1.5 * 1.095 = 1.6425$ mm

For $\alpha = 15^0$

$$L_{nozzle} = \frac{1.095(\sqrt{50} - 1) + 1.6425(see15 - 1)}{tan15}$$

$$\boldsymbol{L_{nozzle} = 25.02\ mm}$$

By assuming the diameter of the chamber is not necessarily equal to the diameter of the nozzle inlet [8]. So here in this the diameter of the nozzle inlet kept constant and the design calculations are started by considering the Length of the chamber is equal to 10cm, 5 cm and 2.5 cm for the constant chamber volume. so the variation of the chamber cross sectional area is calibrated for the constant chamber volume.

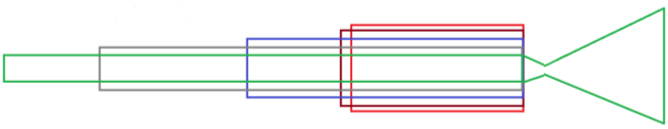

Fig. 1. Chamber volume and Length variation

Table 3. Chamber volume and Length variation

Case 01	Lc= 174 mm	Dc= 4.89 mm
Case 02	Lc= 100 mm	Dc= 6.43 mm
Case 03	Lc= 50 mm	Dc= 9.10 mm
Case 04	Lc= 25 mm	Dc= 12.85 mm
Case 05	Lc= 24.5 mm	Dc= 13 mm

Here in this paper we considered case 05 dimensions of the chamber and CFD simulation is done on this model.

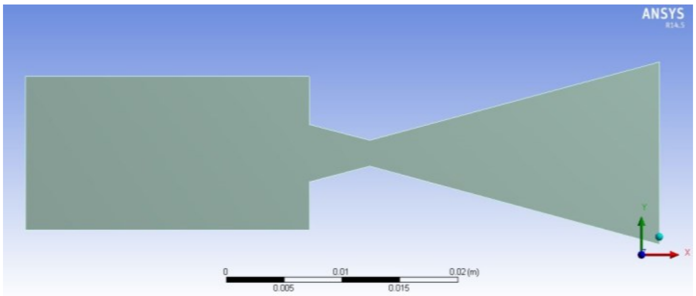

Fig. 2. 2D Chamber model

3. Results

In order to verify the design quality of the nozzle flow field investigation of the nozzle has to be studied. A 2-D axis symmetric computational simulation of the flow field is necessary, which may be either developing a code or by using commercial code. In the present study computation has been made to obtain flow through the nozzle using commercial software FLUENT. In the present study two dimensional structured grids were generated on the nozzle profile. For axis symmetric computation, quadrilateral cells with map scheme was used for grid generation.

The boundary conditions values are taken from NASA-CEA code.

Table 4. Boundary conditions

Parameters	HAN
Pressure inlet in bar	16
Total temperature in K	2295
Material properties (combustion gas) Specific heat in J/Kg-K	2831
Viscosity in Kg/m-s	0.8474E-4
Thermal conductivity in W/m K	0.2502
Molecular weight	22.91

The following results contains the information about the nozzle pressure, velocity, temperature and mach number variation along the nozzle and domain for HAN mono propellant combination. The adiabatic flame temperature of the HAN combustion is around 2294 K. The velocity of the exit gases of HAN combustion is around 2240 m/s. The Results of Nozzle Flow Analysis is tabulated in Table 5.

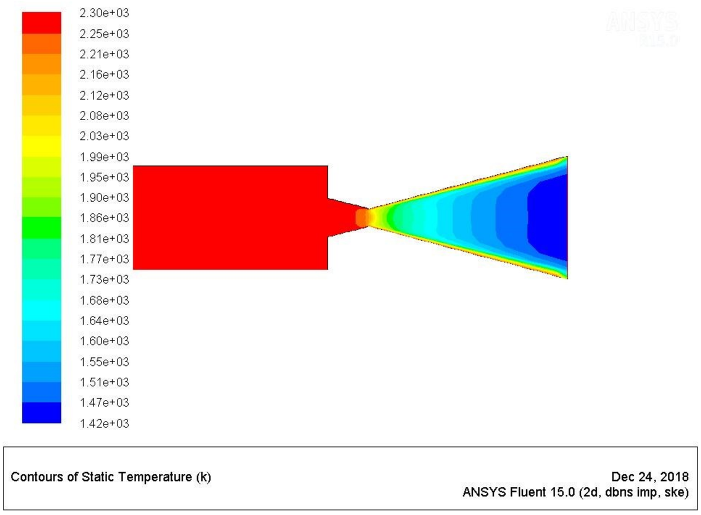

Fig. 3. Contours of Static Temperature

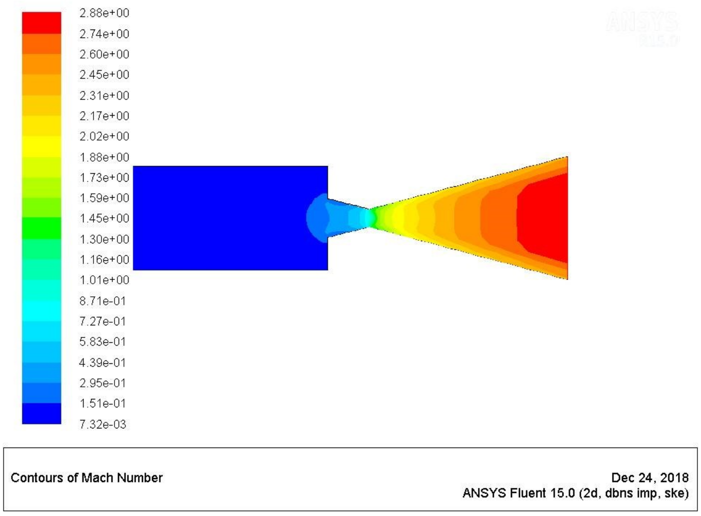

Fig. 4. Contours of Mach number

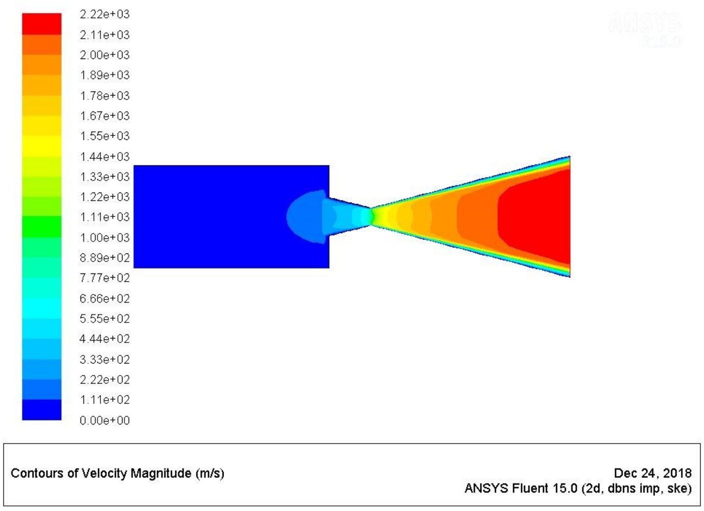

Fig. 5. Contours of Velocity magnitude

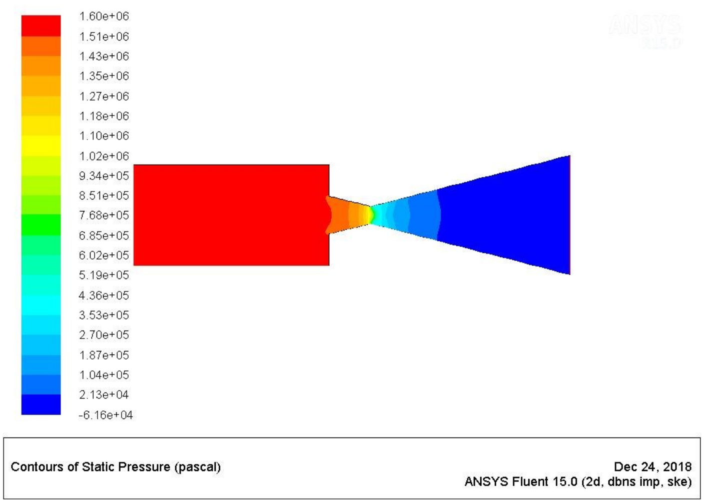

Fig. 6. Contours of Static Pressure

Table 5. Nozzle Flow Analysis Results

Parameters	**From CFD**	**From theoretical**
Temperature at the exit	1420 K	1006 K
Velocity at the exit	2220 m/s	2603
Mass flow rate	5.11 grams/sec	4.27 grams/sec
Thrust	11.34 N	11.12 N
Isp	226 seconds	265 seconds

4. Conclusions

In this work we successfully simulated the rocket performance parameters of small spacecraft reaction control thruster for HAN based mono propellants, analytical calculations and flow simulations are done for the standard size11 N thruster. HAN based mono propellants in AOCS thrusters provide high specific impulse which is suitable for use in spacecraft AOCS operations. For the thrust chamber modeled at 11N of thrust and chamber pressure of 16 bar with the propellant combination of HAN+ Methanol+ AN + H2 O shows a very good consistency when compared with computational results. From the analysis result it is found that monopropellant engine with the propellant combination of HAN+ Methanol+ AN + H2O is suitable for design of spacecraft AOCS thrusters.

Nomenclature

HAN	:	Hydroxyl Ammonium Nitrate
CFD	:	Computational Fluid Dynamics
AOCS	:	Attitude and Orbit Control System
I_{sp}	:	Specific impulse
C_f	:	Thrust coefficient
P_O	:	Camber Pressure

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International Journal of Aviation Science and Technology

Research Article

Modelling and Managing Airport Passenger Flow: A Case of Hasan Polatkan Airport in Turkey

Ilkay Orhan[1]*, Gamze Orhan[2]

[1] *Eskisehir Technical University – Faculty of Aeronautics and Astronautics*
iorhan@eskisehir.edu.tr - 0000-0001-5303-2143

[2] *Eskisehir Technical University - Faculty of Aeronautics and Astronautics*
gozsoy@eskisehir.edu.tr - 0000-0002-3966-1856

Abstract

The airport passenger flow process is an integrated system in which passengers interact with multiple components of the system, and a failure in one component can cause greater disruption in others because of time-related constraints. Airport operators analyse and decide the results by using decision support systems under the airport management strategies by determining the potential congestion and related problems such as capacity limitations or equipment malfunctions. In this study, airport systems handle the passenger flow that covers all activities between the airport entrance and boarding. Discrete event simulation was used to assess the passenger flow and performing the activities in the related processes. The model comprises security screening, check-in, passport control and boarding processes. Within the proposed model, points with potential bottlenecks in Hasan Polatkan Airport have estimated according to International Air Transport Association (IATA) performance values.

Keywords

Airport Management
Decision Support Systems
Simulation
Air Transportation
Airport terminal analysis

Time Scale of Article

Received 6 November 2020
Revised until 13 December 2020
Accepted 17 December 2020
Online date 30 December 2020

1. Introduction

Airports are one of the important components of the air transport industry. Airports are highly complex system comprising interconnected subsystems and places where planning becomes important. Airports are an integrated system comprising departure and incoming passenger flow processes. Depending on the size of the airport, passengers' needs for eating, drinking and shopping may fulfilled as requested. Any failure in the system may affect another system, causing system-wide failures. Decision analysis and planning prevents the problems may occur in airport operations [1].

The airport management weighs the decisions in order to meet the demands of the airline operators within the service and the security criteria determined by the aviation authorities and to implement the suggestions to improve the operational processes. Although the processes at airports are basically similar, services offered at airports may vary depending on the number of passengers and the size of the airport [2]. Because of the annual increase in the number of passengers and flights in airports under normal conditions, the airport's performance may decrease to a certain extent from year to year. The airport management should analyse the reason of the performance decreases and make the improvements at reasonable costs [3].

In parallel with the developments in the airline industry, the airport operator will offer the best service quality with the lowest cost of service. Also, airport operator should keep passenger satisfaction to desired levels by using dynamic facility planning, operational quality, and performance analysis. While passengers can catch their flights on time, they will still have enough time for shopping a little more and other fun activities at the airport, while contributing to the increase in airport operating income. It can change the overall experience

*: Corresponding Author Ilkay Orhan, iorhan@eskisehir.edu.tr, Tel: +90 222 321 3550 Ext:6881
DOI: 10.23890/IJAST.vm01is02.0204

of a traveler at an airport to challenging and time-consuming. Delays occur during parking, check-in, security screening and boarding. Also, the less time the passengers spend in the system, the higher the customer satisfaction [4]. As passengers are the largest source of income for airports, that passengers leave from airports satisfactorily and processes should plan to spend a minimum of time at potential bottleneck points between their entrance to the airport and access to the aircraft [5].

According to a study by Takakuwa and Oyama [6] in the international departure terminal of Kansai International Airport, passengers spend 25% of their total time spent in the terminal building by waiting in queues to complete their flight transactions, and 4% by having their transactions done at check-in counters. The increase in the waiting times of passengers in the terminal building negatively affects passenger satisfaction [7]. Also, it reduces the time during which passengers will wander and shop in duty-free stores and benefit from waiting lounges and other facilities within the terminal building. However, that the passengers travel freely and engage in activities such as shopping or eating and drinking contributes positively to the commercial revenues of the airport. Retail sales revenues, such as shopping from stores, food and beverage revenues, have an important place among the commercial revenues of airports [8]. Takakuwa and Oyama [6] study revealed that passengers spend only 23% of their time in the terminal building to generate commercial income. However, under the influence of psychological factors, the perception of time spent waiting by passengers may be higher than the perception of travel time. Because the perception of "time spent" is higher regarding the periods that have spent without being engaged in anything when it will end is uncertain or not disclosed [9]. Considering all this information, the strategic importance of reducing passengers' waiting times in queues is obvious to airports in terms of both improving service quality perception by positively affecting passenger satisfaction level and creating an opportunity to increase commercial revenues.

In air transport, it is possible to meet the expected future growth rates either by building new airports, by expanding existing airports or by using existing airports more effectively. For this purpose, the system should test continuously, and airport managers should analyse the decisions planned to correct the detected bottlenecks. Analysing each of the implemented improvements by trial and error is not appropriate because of its cost and potential disruption to the workflow. A simulation model should assess and test the system. This study proposes a discrete event simulation as a model that deals with passenger operations in an airport.

2. Literature Review

The performance evaluation of airports has been the subject of comprehensive studies in airport modelling and process optimization. As a result, there are many studies in the literature on the mathematical model and simulation method integrated with decision support systems. Airport managements use these models and tools in the planning, design and operation of land and air side operations for improving the operations such as aircraft, passenger, baggage, and cargo. Zografos et al. [10] have developed an integrated decision support system for airport performance analysis and used various analytical models and simulation tools. Bruno et al. [11] proposed a decision support system for improving airport performance services in order to make more practical and precise planning decisions, by proposing a mathematical model capable of performing check-in decisions by also integrating staff planning considerations. Herrero et al. [12] developed a decision support system that automatically provides the best routes and sequences for aircraft movement on the ground, depending on the operations requested for airport ground controls at Madrid Barajas International Airport. Stamatopoulos et al. [13] developed an integrated decision support system for strategic level airport planning that considers the operations between different parts of the airfield and the dynamic characteristics of the airfield capacity. Hayashi et al. [14] proposed a pushback decision support tool for the airport ramp tower controller for flow management under the current restrictions at the airport. The proposed systems provided the reduction of taxi time by one minute for each flight and helped minimized total consumption of departure flight fuel by 10-12% without limiting runway throughout. Fayez et al. [14] provided a simulation-based decision support system to test airport operations and compare the results of the decisions made.

There are many studies in the literature on the current problems of airport operations and operational performance covering the planning challenges. Beck [16] demonstrated the passenger flow at the new terminal at Heathrow Airport with simulation before the terminal opens. Yamada et al. [17] evaluated the performance of security checkpoints in domestic flights using a simulation model. Kierzkowski and Kisiel [18] investigated the effects of passenger behaviour characteristics of passengers and operators on airport security screening reliability. Dorton and Liu [19] analysed baggage amounts and alarm rates that affect operational efficiency within the queueing network and intermittent event simulation. Manataki and Ografos demonstrated the complexity and stochastic structure of processes in the airport terminal with a simulation model [20]. Sultan considering the stochastic aspects in the simulation, examined the effects of different parameters such as the number of passengers on the plane, counter opening and closing times, and used it with a linear program to reduce the number of counters in the check-in area [21]. Araujo and Repolho [22] proposed a method combining an optimization-based linear programming and simulation to minimize operational costs and found an optimum and opening counter tariff under a given service level. Mota and Zuniga [23] presented a hybrid method that uses an evolutionary algorithm based on passenger behavior to simulate check-in problems. Joustra and Van [24] studied the practical simulation approach to assess check-in at airports. Yan et al. [25] presented a simulation model to assist airport managers/operators to test the effects of random flight delays on static gate assignments, and random buffer times and real-time gate assignment rules. The proposed simulation model created in the experimental study using the data of Chiang Kai-Shek Airport in Taiwan. Dorndorf et al. [26] examined the studies on the gate assignment problem.

3. Research Aims and Methodology

3.1. Aims

The primary purpose of this research is to assess the effectiveness of airport management strategies at points where passenger flow occurs in an international airport, within the framework of the passenger satisfaction criteria determined by IATA. The proposed model that can accurately detect potential bottlenecks in passenger processes with a simulation approach and increase operational efficiency.

Airports are facilities that meet the needs of passengers and airlines. Airport managements dynamically change and apply the current and updated regulations at points in passenger service processes to sustain the best service quality. It is necessary to examine the contribution of decisions made and changed in practice to the potential bottleneck points at the airport and the system performance holistically, thus preventing unforeseen negative cases.

Decision-making is not the settlement of discrete disputes, but in a complex setting, continuous management of the state of affairs [27]. The decision support system is an information system that establishes and/or solves the models involved in a decision process, enabling the decision maker to assess the methods, models and algorithms of management science and operations research together with decision and utility theory, and designed to contribute to the quality of the decision [28].

A decision support system comprises user interface, model management, model solver and databases. Figure 1 shows the flowchart of a decision support system proposed within this study. The database contains information such as personnel working schedule, airport flight schedule, number of arrival and departure passengers, resources (such as X-ray, and check-in desk). Model management takes certain information from the database and runs a model according to the decision-maker's preference and presents the model results to the decision-maker with a user interface. The decision makers assess the results from solvers such as ARENA and runs different models until they satisfy with the results. When the airport manager decides that the results are appropriate, it takes a detailed report from the decision support system and applies the model's solutions. Before deciding about the changes in the system, the decision-maker should reveal holistic effects and relationships about the decisions and contribute the system in line with the specified goals and expectations.

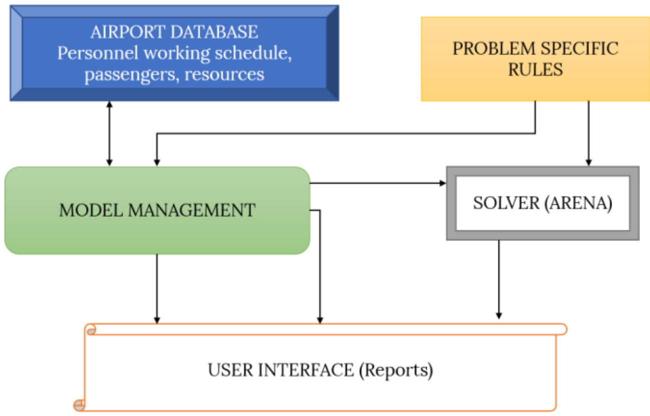

Fig. 1. Flowchart of the decision support system

3.2. Methodology

The follow-up and flexibility of the plans created for airport operations are also important. The decision-makers should analyse the plans created for airport operations for different conditions that may occur to keep the highest service quality. They also should assess different conditions and considered alternative action plans by the question "what if analysis". Performing all analyses by trial and error is not appropriate because of many reasons, especially cost. Therefore, the modelling model through the imitations of the system should use for analysing the system.

Using the simulation method, it is possible to analyse a complex system without disturbing the operation of the actual system and to compare it with its alternatives. Considering the complex system structure of the airports, simulation models come to the fore as suitable tools for the analysis of such a system.

Although the proposed model within this study is general, it only covers the departing passenger processes. The decision-maker can assess the performance analyses and the waiting times by adding/removing personnel to the system, adding/removing X-rays in the model, and use the resources more efficiently. Decision support system ensures the assessment of the effectiveness and results of the decision taken by the criteria for passenger satisfaction and airport operating strategies. The simulation results provide some performance metrics such as bottleneck points, average waiting time, the average queue length. A discrete event simulation and the first come first served (FIFO) principle applied for the modelling of this study.

The most appropriate method in modelling complex processes combined with a limited capacity infrastructure is simulation. One process whose stochastic structure best suits this is the flow of airport passenger traffic. As in some studies used to characterize the complex processes at the airport, the simulation analyses performed by Rockwell Arena in this study [24, 27, 28, 29].

Table 1. Level of service [30]

Level of Service (LOS)	Level	Average Waiting Time (minute)
A	Excellent comfort	< 1
B	Hight comfort	1-17
C	Good comfort	17-34
D	Adequate comfort	34-58
E	Inadequate comfort	> 58

IATA has defined Level of Service (LOS) for monitoring operational service performance at airports and planning new facilities. A grading system from A (excellent comfort) to E (inadequate comfort) is used to determine the level of service. Table 1 shows the level of service according to flow, delay and comfort [30].

System administrators and designers should specify the desired or required LOS. The recommended minimum level of service is the level of C. During the confusion times, the acceptable level of service is the level of D [31].

3.3. Model Architecture

After passengers pass the security checkpoint at the airport, they go to the check-in counter or kiosks for ticket approval and baggage delivery. After the passport control stage for international flights, passengers pass through a second security check for the passage to the secure area for boarding and pass to the boarding or gate area.

The departure and arrival passenger flow procedures of the airport are different. The process passengers go through at the airport before their flight is more important, as it has a greater impact on the entire operation of the terminal and on other aspects of the airport.

The classification of departure passengers in the terminal building is as follows [32]: Terminal entrance security check, ticket control, interfaces (eating, drinking, shopping), passport control, waiting room, gate control, boarding the aircraft.

Terminal entrance security check

Entering the terminal building, the passenger proceeds towards the security point. This unit is a processing unit. Each passenger passes from the security check one by one. The terminal entrance security control is the stage where security procedures such as checking all the luggage of each person entering the airport on the x-ray device, passenger security control, turning on and off devices such as computers.

Checking Counter

Checking counter is a unit of processing. The number of counters required for ticket control depends on the duration of a passenger's ticket control and the distribution of passengers to the ticket control point. Passengers deliver their luggage and receive their boarding pass at check-in counter [33]. Every passenger should have completed the check-in process before passport control. At some airports, the passenger does check-in using kiosks, independent of the airport personnel. There is not a kiosk at Hasan Polatkan Airport.

Interfaces

Interfaces are places such as eating, drinking, and shopping areas. These venues cover small areas in small airports. These units are also waiting units. Passengers can spend time in these units or pass without stopping at the units. There is a food and beverage area in the international flights section of Hasan Polatkan Airport that passengers can use. Although passengers can benefit from interfaces before passport control at small airports, they can use them both before and after passport control at large airports.

Passport Control

Passport control unit is a processing unit, like ticket control unit. Unlike the ticket control unit, the passport control unit is not available at the domestic terminal. The queue and passenger movements proceed according to the sequence formed by the passengers in the processing units. There are two passport control points in the international flights department of Hasan Polatkan Airport.

Waiting room

Passengers passing through the gate control go to the waiting room and wait in this area until the airlines/airport personnel let them to go to aircraft. Since this space is a waiting area, the level of service for the area is measured by the number of people per square meter.

Gate control

It is one of the flight gate control point processing units. The feature that distinguishes this unit from other control points is that the number of control points is unique. Therefore, the waiting time at the checkpoint is longer. Passing through the flight gate control, the passenger reaches the last waiting room before boarding the plane.

Boarding

It is the point where passengers directly go to the plane with the official's announcement and permission by walking or by bus according to aircraft location at the airport. The average processing time varies with each airport.

3.4. Hasan Polatkan Airport

Hasan Polatkan Airport was first opened to air traffic on March 29, 1989 under the name of "Anadolu Airport" and is an international airport operated by the Faculty of Aviation and Space Sciences on behalf of Eskisehir Technical University Rectorate. International Civil Aviation Organization (ICAO) and IATA code of airport is LTBY and AOE, respectively. The airport primarily aimed to meet the national and international air transport demand that may occur in Eskisehir and surrounding provinces with the educational activities of the Faculty of Aviation and Space Sciences. Hasan Polatkan Airport started international flights in May 2005. Eskisehir Technical University pilot flight training, VIP/CIP flights, air taxi and ambulance flights, training flights of private flight schools, scheduled/non-scheduled domestic passenger transportation flights, scheduled/non-scheduled international passenger transportation flights carry out at airport.

Hasan Polatkan Airport terminal used for international and domestic traffic is 4000 m² in total and comprises two floors. There are two passport control cabins at the transition from the departure passenger section to the sterile lounge.

Figure 2 and Table 2 show the number of commercial passengers and commercial aircraft traffic between 2015 and 2019 for Hasan Polatkan Airport, respectively [34].

Table 2. The number of commercial passengers at Hasan Polatkan Airport between 2015 and 2019 [34]

Year	Domestic	International	Total
2015	2,389	49,536	51,925
2016	1,057	55,397	56,454
2017	1,808	78,240	80,048
2018	787	98,544	99,331
2019	657	88,365	89,022

3.5. Parameters and Assumptions of the Model

Simulation is one of the most useful tools for predicting the relationship and interaction between processes at the airport. Passengers behave differently because their personal and physical characteristics are independent from each other. Simulation is an important tool in modelling passenger behaviour, determining the number of personnel and technical equipment used, analysing the changes depending on the week and passenger density [27].

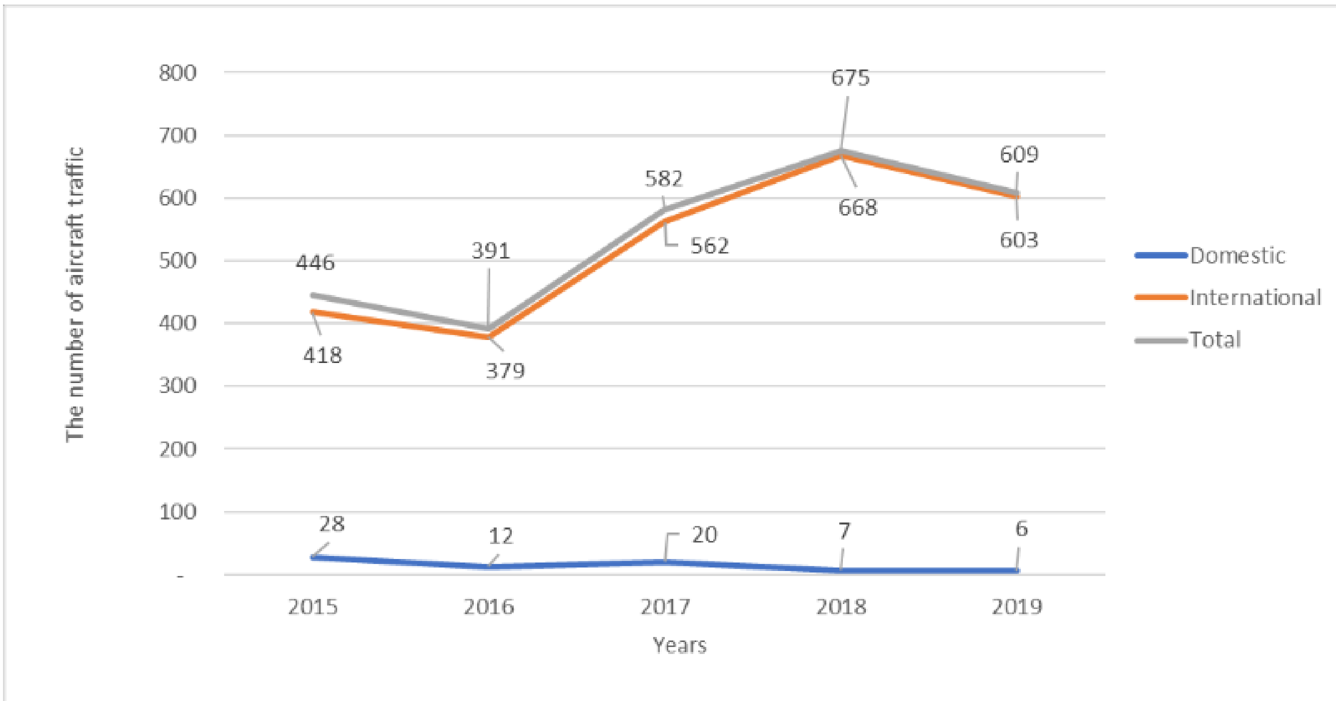

Fig. 2. The number of commercial aircraft traffic at Hasan Polatkan Airport between 2015 and 2019 [34]

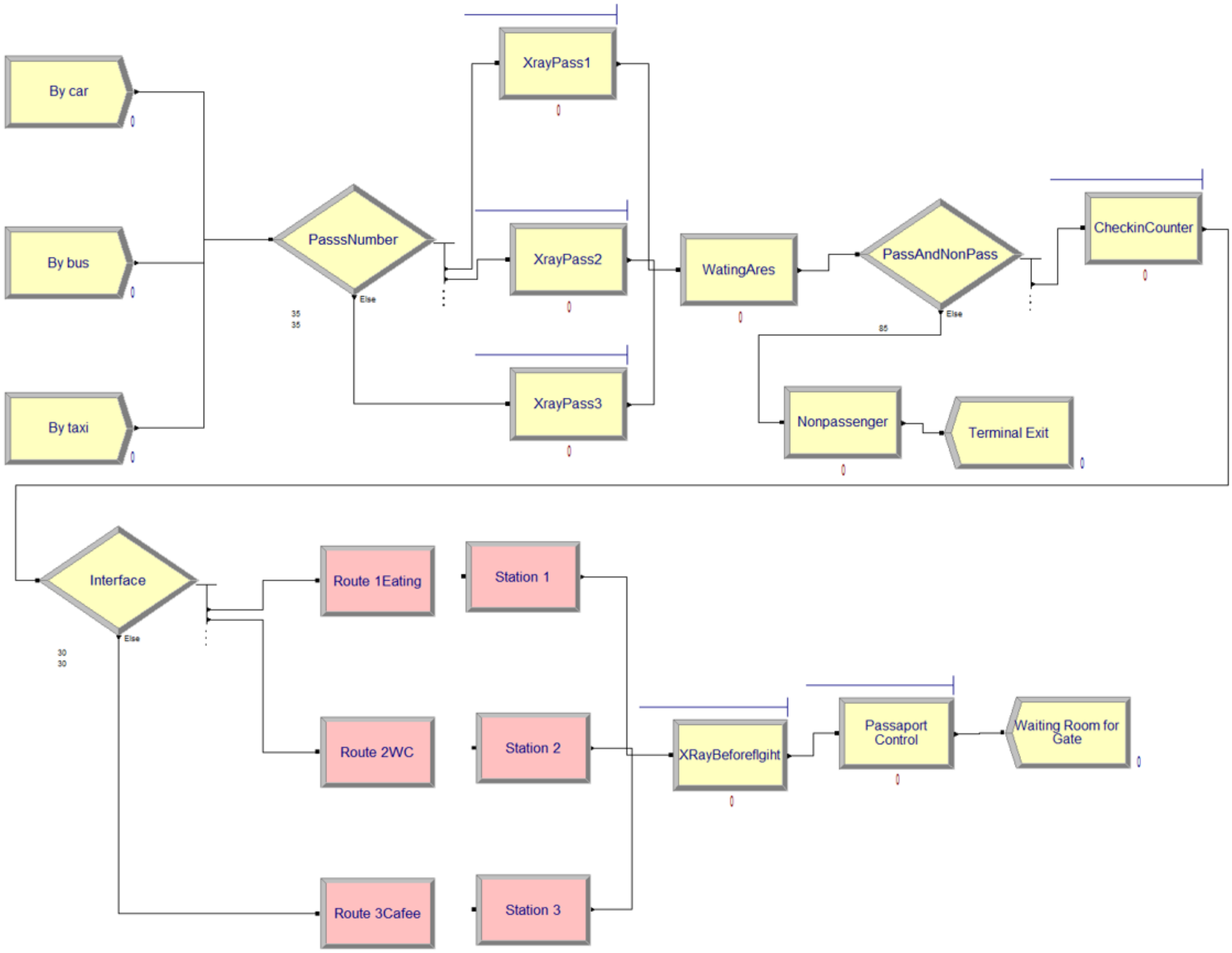

Fig. 3. The simulation model

The following assumptions considered in this study.

- Charter flights are available at the airport. All passengers travel in economy class.
- Passengers arrive at the airport by using their own private vehicles, buses and taxis, with rates of 36%, 24% and 40% respectively [35].
- Passengers arrived by their own vehicles or left by their relatives to the airport have EXPO (2) minutes between arrivals 3 hours before the flight starts, and the passengers arrive with a probability of 20%, 40%, 20% and 20% respectively 1, 2, 3 and 4.
  - Passengers coming by bus arrived at the airport 180 to 210 minutes before the flight and have a uniform distribution. The number of people coming by bus was 45 people on average with Poisson distribution.
  - The taxi arrived between 2 and 2.5 hours before the flight, with 40% and 60% probability. They were also 1 and 2 persons respectively and EXPO (2) minutes between arrivals.
- Since there is no kiosk at the airport, all passengers use check-in counters for ticket and baggage procedures.
- Passengers' baggage count is between 1 and 3. The processing time at the terminal entrance security check is 30 seconds for each baggage.
- 10% of the people entering the airport are the departure passenger's relatives.

Check-in counter and pre-flight final X-ray security control processing times are given in Table 3 [28].

Table 3. Observed Service Times for Passenger Processing Facilities at Airports [36]

Component Type	Service Rate per Passenger (second)	Standard Deviation
Ticketing and baggage		
Manual with baggage	180–240	60
Manual without baggage	100–200	30
Baggage only	30–50	10
Security		
Hand-check baggage	30–60	15
Automated	30–40	10

Figure 3 shows the simulation model established according to assumptions. In the simulation model, incoming passengers have different check-in service times according to the number of passengers and their baggage. The simulation has considered the walking distance from the check-in point to the cafe and waiting area.

4. Case study

The simulation model applied to Hasan Polatkan International Airport, considering the observations made at the airport and the parameters in the literature. Passengers entering the airport after the X-ray security checks go to the airport lounge or airport retail spaces. Passengers who complete their ticket and baggage procedures proceed to the passport processing stage. After completing the second X-ray security checks for hand luggage before the flight, they pass to the waiting room where they will wait until boarding the plane.

The airport provides services to an airline company that performs charter flights. Passengers arrive at the airport 3.5-4 hours before the flight on international flights. Passengers reach the airport in a certain period by using different means of transportation.

At the x-ray security point, which is the first entry point of the passengers to the airport, 2 devices serve and 4 officers work on each device. It is the number of luggage that mainly affects passengers' transit times. Passengers went through security checks with a minimum waiting time of 6.20 minutes, maximum 27.74 minutes and an average of 15.57 minutes and an average of 9 passengers waiting in the queue. When the airport served with a single X-ray device at the entrance, the average number of people waiting in line increased to 43.69 people and the waiting time increases to 68.88 minutes. According to these results, the simultaneous service of both x-ray devices at the airport entrance reveals its importance to prevent an important bottleneck point. The simulation study showed that when 2 x-ray devices served at the x-ray security point, the IATA service level was at the "high comfort" level.

The operation phase with the longest queue length and the longest waiting time is the check-in counter. The check-in counter is the stage where passengers arrive a certain time before the departure time, show their boarding cards or reservation codes (PNR code) to the staff at the counter, complete the acceptance procedures, and the airline employee at the counter prints the boarding card required for boarding. At the counter, passengers can make seat changes, baggage delivery, special service requests, and check-in. Therefore, it is the stage where passengers spend the most time. If four check-in counters served according to the accepted parameters, the average waiting time in the system is 38.78 minutes, ranging from 28.99 to 48.61 minutes. The average number of people waiting in line was 26, with a minimum and maximum number of 22 to 32 people. If five check-in counters served instead of four, the waiting time decreased by 76.32% to 9.18 minutes. However, if four check-in counters serve instead of four, the waiting time increased by 92.70% to 74.73 minutes. According to the data within the study and the results of the simulation, five counter desks should serve in order to increase the service level from "adequate comfort" to "high comfort" in the check-in counter phase.

The average waiting time during the last security check phase before boarding to aircraft and passport control processes performed before the transition to the clean area is less than one minute. These two stages are at the "excellent comfort" level in terms of performance evaluation of IATA. Passengers wait in the queue at the check-in stage. The short processing time in the next process stages contributes to the completion of the subsequent processes without queuing and waiting time.

5. Conclusions

Airport managers consider the capacity and conditions of the airport in the decision processes of operations. Since passengers who want to make the best use of the day at airports prefer flights that take place, especially in the morning and evening hours, there is a certain density in these time periods. Airport managements often make plans to overcome the density, using their experience. It is important for decision-makers to assess their decisions. The improvement or solution proposal for one point can cause a bottleneck at another point. However, it is possible to minimize the potential problems and analyse the decision taken by simulating the operations at the airport.

The proposed simulation model allows the decision maker to analyse all processes and potential bottleneck points in international passenger operations of an airport. It also allows the decision-maker to assess the waiting time and queue lengths in the system and enables the best usage of airport resources.

Simulation is one of the most useful tools for predicting the relationship and interaction between processes at the airport. Passengers behave differently because their personal and physical characteristics are independent from each other. In modelling passenger behaviour, simulation is an important tool to analyse the changes of personnel and technical equipment used in the process depending on the week and passenger density.

There is a need for simulation-based decision support systems that assess the results and effects of decisions taken to manage operations at airports. Considering the increase in airline traffic expected nowadays and, in the future, the integrated systems will ensure that total performance, quality and passenger satisfaction at a high level and the potential bottleneck points prevent.

CRediT Author Statement

Ilkay Orhan: Conceptualization, Data curation, Methodology, Software, Visualization, Investigation, Validation, Writing-Original draft preparation, Writing-Reviewing and Editing. **Gamze Orhan**: Conceptualization, Data curation, Writing-Original draft preparation, Investigation, Validation, Writing-Reviewing and Editing.

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International Journal of Aviation Science and Technology, Volume 1, Issue 2, (2020), 80-91

International Journal of Aviation Science and Technology

Research Article

A Comparative Study on the Tuning of the PID Flight Controllers Using Swarm Intelligence

Aziz Kaba[1]*

[1] *Eskisehir Technical University – Faculty of Aeronautics and Astronautics,*
azizkaba@eskisehir.edu.tr - 0000-0003-0453-2912

Abstract

QUAVs have some shortcomings in terms of nonlinearities, coupled dynamics, unstable open-loop characteristics, and they are prone to internal and external disturbances. Therefore, control problem of the QUAVs is still an open issue. Designed controllers based on the linear dynamics have limited operating ranges. Therefore, nonlinear dynamics of the QUAVs must be derived and used in the control problem. Although some advanced controllers are presented for QUAV control, PID controllers are the most employed, well-known controllers with the simple structure, ease of implementation, solid functionality and robustness amongst the variations up to a degree. In this paper, PID based controllers are proposed for the nonlinear attitude dynamics to overcome the control problem of the QUAVs. However, since optimality and tuning of the PID controllers are fuzzy because of trial and error approaches, swarm intelligence based meta-heuristic algorithms (ABC, ACO and PSO) are employed to optimize the PID coefficients. Results are compared in terms of transient analysis and MC analysis to cover the rise time, settling time, percentage overshoot, steady-state error for the former and stochastic fitness evaluation for the latter, respectively.

Keywords

UAV
Quadrotor
PID Control

Time Scale of Article

Received 21 December 2020
Revised until 25 December 2020
Accepted 27 December 2020
Online date 30 December 2020

1. Introduction

1.1. Background

PID controllers can treat both the transient and steady-state responses of a plant. PID can be considered as the simplest yet the most efficient controller. As the name implies, it has just a three-parameter configuration space to fit the control specifications. First applications of the PID controllers date back to the beginning of the 20th century, and they gain more popularity with the proposition of the ZN tuning method [1]. Although many novel and advanced controller designs have being proposed, PID controllers are still the most widely-used control method in industrial systems [2]. There are many advantages of the PID controllers such as low-implementation efforts, wide operating range, simple structural design and robustness against disturbance sources [3, 4]. PID and its variants (PI, PD, etc.) are being employed as the standard controller at the lowest level of the process controllers and at the higher level of the engineering areas with over 90% ratio [5, 6].

1.2. Related Works

There are so much research efforts that went into the modern extensions of the PID controllers. Among them, some recent high-level implementations of the PID controllers can be given as follows. PID control design for an inverted pendulum is given in [7]. A fuzzy self-tuning PID algorithm for three-dimensional bio-printing temperature control system is proposed in [8]. An adaptive PID control algorithm for the second order nonlinear systems is derived in [9]. Extremum seeking nonlinear PID based pressure control algorithm is given

*: Corresponding Author Aziz Kaba, azizkaba@eskisehir.edu.tr Tel: +90 222 321 35 50 #6872
DOI: 10.23890/IJAST.vm01is02.0205

in [10]. Fuzzy PID attitude control of a vehicle is considered in [11]. An adaptive PID controller is presented in [12] for controlling speed of a brushless DC motor. Another speed control application is proposed in [13] using intelligent PID control with applications to an ultrasonic motor. Z-axis position control of a servo system for laser processing is achieved via fuzzy PID control in [14]. PID control of a flexible manipulator is presented in [15] with an opposition based spiral dynamic method. A double fuzzy RBF-NN based PID control for 7-dof manipulator is proposed in [16].

Extensions and improvements of the PID controllers are also applied as the flight controllers because of aforementioned many advantages. A data driven PID controller implemented on a FPGA with applications to UAV is detailed in [17]. According to the work, the presented controllers can control the new generation of intelligent UAVs that can perform their assigned tasks with no human intervention. A fused PID control strategy is presented in [18] for a tilt-rotor VTOL aircraft. There are two different PID controllers that comprise fixed-wing and rotary-wing parts according to the mode of flight. According to the results, the proposed fused PID controllers make a smooth transition between the flight modes. A simple adaptive PID based fault-tolerant flight controller is proposed in [19]. The method is validated with a numerical example and a flight test. According to the results, performance of the system can be improved compared to the classical PID controllers. A PID speed controller is proposed in [20] for a small-scale turbojet engine where a modification is added to the classical controller scheme. A low-pass filter is added to the differential term to reduce the noise in case of high frequencies. Results show that the controller is effective for steady-state loading changes. An enhanced PID controller for fault tolerant control of a quadrotor is proposed in [21]. The controller is tested against the actuator faults of the quadrotor. Enhanced PD structure is based on the saturation of the integral term to overcome the anti wind-up. An attitude controller based on PD and KF is proposed in [22] for a quadrotor. The measurement and modelling errors are eliminated by KF and system states are controlled by the PD controller, respectively. Results show that the proposed method overcome the disturbances with a small residual error rate.

PID and its variant controllers are prone to some shortcoming such as parameter tuning and uncertainty about it [23]. There are some works devoted to the tuning of the PID controllers. A PSO based PD flight control system is proposed in [24] for an aircraft. The results of the method are compared with that of P, PD, PI, and fuzzy controller. Analysis show that with the proposed method much better results can be obtained compared to classical approaches. Another application of PSO optimized PID flight controller is given in [25] for altitude control of a quadrotor. Better altitude control responses are achieved with implementing the PSO based PID controller. An improved BP based NN PID control is presented in [26] with application to flight tracking control of a UAV. Both the BP based NN and the PID controller are optimized with GA to obtain the ideal parameters. Results show that the proposed method handled the attitude tracking control with robustness. A DE based PID control is presented in [27] for hover position of a quadrotor. A hybrid performance index is proposed in the paper where the proposed method improved the performance index with faster rise time and minimum overshoot, respectively.

Based on the above discussion, it can easily be said that the PID controllers have being employed for over decades in process control and they have being improved with the developing technology. Applications of PID controllers are also widely employed in aircraft and UAV control problems. However, because of complexity of the flight dynamics such as coupled translational and rotational motions on quadrotors, it is getting harder to tune the PID parameters by trial-and-error approaches. There are some works devoted to this area. So, in this work, a comparative study that is based on the swarm intelligence methods, namely particle, bee and ant swarms, is conducted. Optimality, performance and analyses are validated for a nonlinear quadrotor UAV model.

Organization of the paper as follows. The mathematical model of the quadrotor is derived in Section 2. The swarm intelligence and implemented algorithms (ant colony optimization, artificial bee colony and particle swarm optimization) are given in Section 3. PID controller structure is given in Section 4. Results and Discussions are covered in Section 5. Last, conclusions are given in Section 6.

2. Mathematical Model

Quadrotor UAVs have being employed in a wide range of applications from search and rescue, surveillance, aerial photography, to climate forecasting by military, industry, and also hobbyists, respectively. QUAV comprises four rotors that are placed on the corners of the rigid cross-type frame as seen in Figure 1.where $\{F_i \mid i = 1,2,3,4\}$ is the set of net forces that are produced by the each rotor, B is the body-fixed frame, E is the earth-fixed (inertial) frame, $\{x_b, y_b, z_b\} \in \mathbb{R}^3$ are the axis elements of the B, $\{x_i, y_i, z_i\} \in \mathbb{R}^3$ are the axis elements of the E, $\{\theta, \phi, \psi\}$ is the set Euler angles defined in E, and lastly mg is the weight of the QUAV, respectively.

The curved arrows show the directions of the rotors. Two rotors are rotated at clockwise direction while others rotate at counter-clockwise direction, respectively. In a balanced flight, the rotor pairs rotate at the same speed. Since QUAVs do not have any servo based flight surface controllers, both translational and rotational motions are created with the difference between the rotors. However, it is worth to mention that since QUAVs are under-actuated vehicles because of inequality between inputs and outputs of the MIMO system, translational motions of the $\{X, Y\}$ states are achieved through employing the attitude angles. Roll angle ϕ is generated by the difference of rpm between the 2nd and 4th rotors, pitch angle θ is generated by the difference of rpm between the 1st and 3rd rotors, and lastly yaw angle ψ is generated by the difference of rpm between the rotor pairs, respectively. The translational motion set $\{X, Y, Z\}$ is in $[m]$ and attitude angles $\{\theta, \phi, \psi\}$ are in $[rad]$.

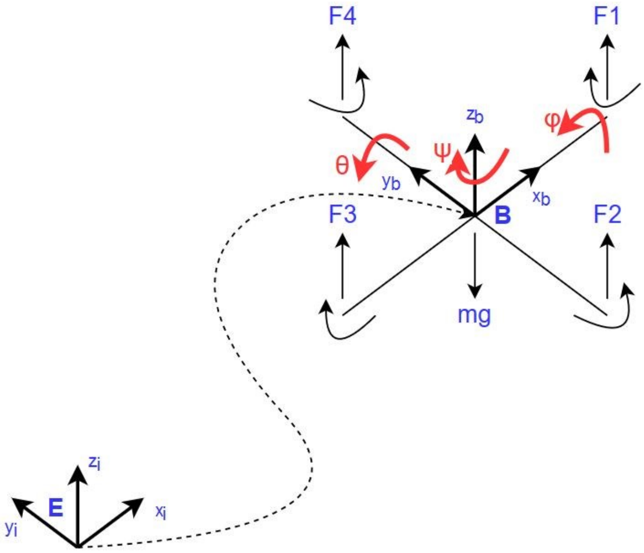


Fig. 1: Coordinates and forces acted on a QUAV

In order to transform a set of vector v defined in one reference frame $(v \in \mathbb{R}^3)$ to another reference frame $(\acute{v} \in \mathbb{R}^3)$, three sequential rotation is needed. A transformation between **B** and **E** frames via (ψ, θ, ϕ) rotation sequence can be obtained by Eqs. (1-3).

$$R(\psi) = \begin{bmatrix} cos\psi & sin\psi & 0 \\ -sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$R(\theta) = \begin{bmatrix} cos\theta & 0 & -sin\theta \\ 0 & 1 & 0 \\ sin\theta & 0 & cos\theta \end{bmatrix}$$

$$R(\theta) = \begin{bmatrix} cos\theta & 0 & -sin\theta \\ 0 & 1 & 0 \\ sin\theta & 0 & cos\theta \end{bmatrix} \quad (2)$$

$$R(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\phi & sin\phi \\ 0 & -sin\phi & cos\phi \end{bmatrix} \quad (3)$$

where R is the rotation. By multiplying the orthogonal rotation matrices given in equations. (1-3), the final rotation matrix is obtained in Eq. (4) as follows.

$$\boldsymbol{R} = \begin{bmatrix} c\theta c\psi & s\theta s\phi c\psi - s\psi c\phi & s\theta c\phi c\psi + s\psi s\phi \\ c\theta s\psi & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \quad (4)$$

where c is the abbreviation of cosine and s is the abbreviation of sine, respectively. The multiplication of orthogonal matrices is also an orthogonal matrix and reverse transformation can easily be obtained with the following equation.

$$\boldsymbol{R_i} = \boldsymbol{R}^{-1} = \boldsymbol{R}^t \quad (5)$$

where subscript $\boldsymbol{R_i}$ denotes the inverse rotation, $\boldsymbol{t}$ is the transpose operator and (-1) is the inverse operation defined in matrices. Since body rates $\{P, Q, R\}$ are measured at **B** but Euler rates $\{\dot{\phi}, \dot{\theta}, \dot{\psi}\}$ are defined in **E**, a coordinate transformation is needed and can be obtained by using Eq. (6) and reverse transformation can also be achieved with Eq. (7).

$$\begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\phi & s\phi c\theta \\ 0 & -s\phi & c\phi c\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & s\phi tan\theta & c\phi tan\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi sec\theta & c\phi sec\theta \end{bmatrix} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \quad (7)$$

The angular acceleration equations can be obtained through the moment equation and given in Eq. (8).

$$\begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} = \begin{bmatrix} \frac{(I_y - I_z)}{I_x} QR \\ \frac{(I_z - I_x)}{I_y} RP \\ \frac{(I_x - I_y)}{I_z} PQ \end{bmatrix} + \begin{bmatrix} \frac{l(F_2 - F_4)}{I_x} \\ \frac{l(F_1 - F_3)}{I_y} \\ \frac{d}{b}(F_1 - F_2 + F_3 - F_4) \end{bmatrix} \quad (8)$$

where I_x, I_y, I_z are the moment of inertias of the QUAV, b is the thrust coefficient of the propellers and $\dot{P}, \dot{Q}, \dot{R}$ are angular accelerations. There are four inputs for the QUAVs comprise of roll, pitch, yaw and altitude control which are defined in Eqs. (9-12), respectively.

$$u_z = \sum_{i=1}^{4} F_i \quad (9)$$

$$u_\phi = l(F_4 - F_2) \quad (10)$$

$$u_\theta = l(F_3 - F_1) \quad (11)$$

$$u_\psi = d(F_1 - F_2 + F_3 - F_4) \quad (12)$$

where l is distance between the center of the gravity of quadrotor and center of propeller, d is the ratio between the drag and the thrust coefficients of the propeller, u_z is control input of the altitude u_ϕ is control input of the roll angle, u_θ is control input of the pitch angle, and lastly u_ψ is control input of the yaw angle, respectively.

Nonlinear attitude dynamics of the QUAV regarding angular rates (without disturbances) are given in Eqs. (13–18).

$$\dot{P} = \left[\frac{(I_y - I_z)}{I_x} QR + \frac{1}{I_x} u_\phi\right] \quad (13)$$

$$\dot{Q} = \left[\frac{(I_z - I_x)}{I_y} RP + \frac{1}{I_y} u_\theta\right] \quad (14)$$

$$\dot{R} = \left[\frac{(I_x - I_y)}{I_z} PQ + \frac{1}{I_z} u_\psi\right] \quad (15)$$

$$\dot{\phi} = P + Qs\phi tan\theta + Rc\phi tan\theta \quad (16)$$

$$\dot{\theta} = Qc\phi - Rs\phi \quad (17)$$

$$\dot{\psi} = Qs\phi s\theta + Rc\phi sec\theta \quad (18)$$

3. Swarm Intelligence

Swarm Intelligence is a concept that deals with the designing of algorithms or distributed problem solvers inspired by the collective behaviour of social insect and animal societies [28]. The swarm term is used not only for social insect species but also used in a common meaning that focus on any restrained population of interacting individuals [29]. Typical examples of swarms can be bee colonies, ant colonies, flock of birds, swarm of cells, and fish swarms. By inspiring from aforementioned colonies, researchers proposed many swarm intelligence methods to deal with the engineering problems. Some well-known swarm intelligence algorithms are PSO [30], ABC [31] and ACO [32].

According to the [29], necessary and sufficient properties for the swarm intelligence methods are self-organization and division of labour. Self-organization property can be defined as the reflections of the interactions from the lowest-level to the global scale. The property must ensure that the interactions must be executed with local information with no governing relation from the global level. Self-organization property relies on the following properties [28].

- Positive feedback,
- Negative feedback,
- Fluctuations (random walks and errors),
- Minimal density of mutually tolerant individuals.

On the other hand, division of labour property is defined as the performing of different tasks simultaneously by the individuals that are experts on the related task. Thus, efficiency of the task performances is increased compared to the sequential tasks performed by the individuals that are not experts on the related task [33].

Ant Colony Optimization

ACO is an optimization method models the swarm of ants that is based on the natural behaviours of the ant colonies and worker ants. When individual ants forage to find a profitable food source, they find an effective route between the nest and food source. These natural behaviours can be modelled to design an optimization algorithm to solve the engineering problems with an optimum solution. The interactions between the ants rely on the pheromone they release. When ants walk from the nest to a food source, they use different routes. They release pheromone while they walk. The pheromone is a scent that attracts the other ants and decays. The stronger the pheromone, the more ants are attracted. So, if any of the ants returns quicker than the others with a food, the route that the ant used has stronger pheromone trace behind it. Thus, other ants will instinctively follow this shorter route because of stronger pheromone properties. When more ants used the route, the more pheromone is added, which leads attraction of more ants [34]. This effect is called as *stigmergy* that has two main distinct characteristics from other forms of communications as follows.

- Stigmergy is an indirect form of communication that its media is environment,
- Stigmergy is a local form of communication that only the nearby insects can access.

Stigmergic communication in the ant colonies depends on the concentration of the pheromone. If ants perceive higher concentration of pheromone, they follow this path thus ant colony can transport food sources into the nest efficiently [35].

Another important property that ACO simulate from real ant swarms is autocatalysis. Since the pheromone deposited by the ants is decayed over time, if the path between the nest and food source is shorter than more pheromone is deposited, which leads more ants to use the shorter path [36]. This behaviour belongs to the exploitation of positive feedback, in which more ants will produce higher pheromone concentration results with more ants in that shortest or optimal path.

The pheromone updating rules of ACO for the TSP problem can be given in Eqs. (19-21) [37].

$$\tau_{ij}(t+d) = (1-\rho) * \tau_{ij}(t) + \rho * \Delta\tau_{ij}^{+} \quad (19)$$

$$\Delta\tau_{ij}^{+} = \frac{1}{L^{+}} \quad (20)$$

$$\tau_{ij}(t+1) = \xi * \tau_{ij}(t) \quad (21)$$

where $\rho \in (0,1)$ is the persistence of pheromone trails, $(1-\rho)$ is the evaporation rate, d is the number of variables, $\Delta\tau_{ij}^{+}$ is the amount of pheromone increase of elitist ant, L^{+} is the length of the solution of the elitist ant, and ξ is an adjustable parameter where $0 < \xi < 1$.

The flowchart of the ACO algorithm is given in Figure 2. Algorithm starts with initialization of the parameters, constraint definition etc. Ants are randomly located in the search space. Then ants look for food sources. Their pheromone is updated and evaporated according to the time and length of the path. If conditions are satisfied (such as minimum objective function value) or exceeded (such as maximum number of iterations), the ACO algorithm is terminated. The results are stored, and the algorithm is finished.

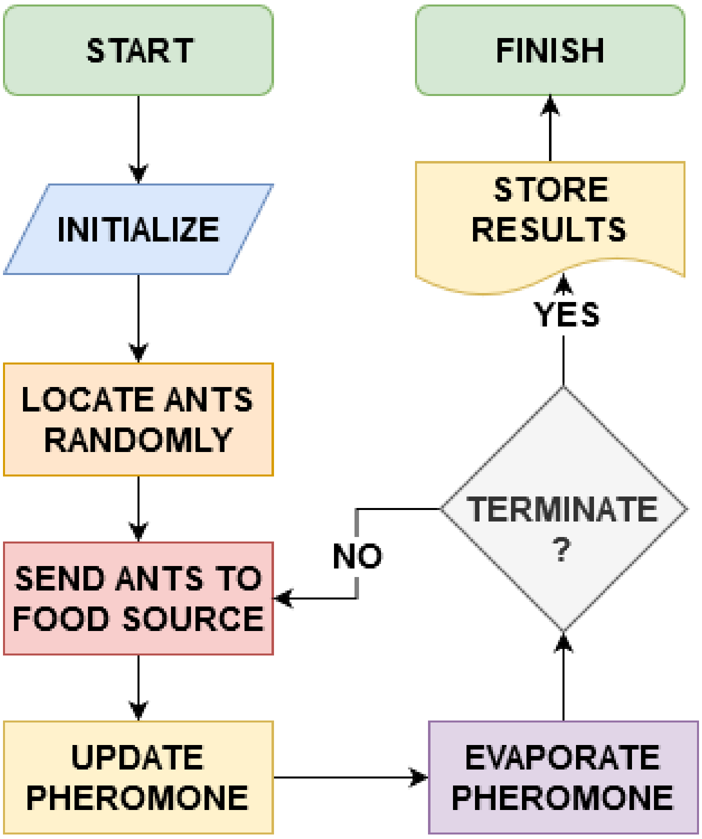


Fig. 2: Flowchart of the ACO algorithm.

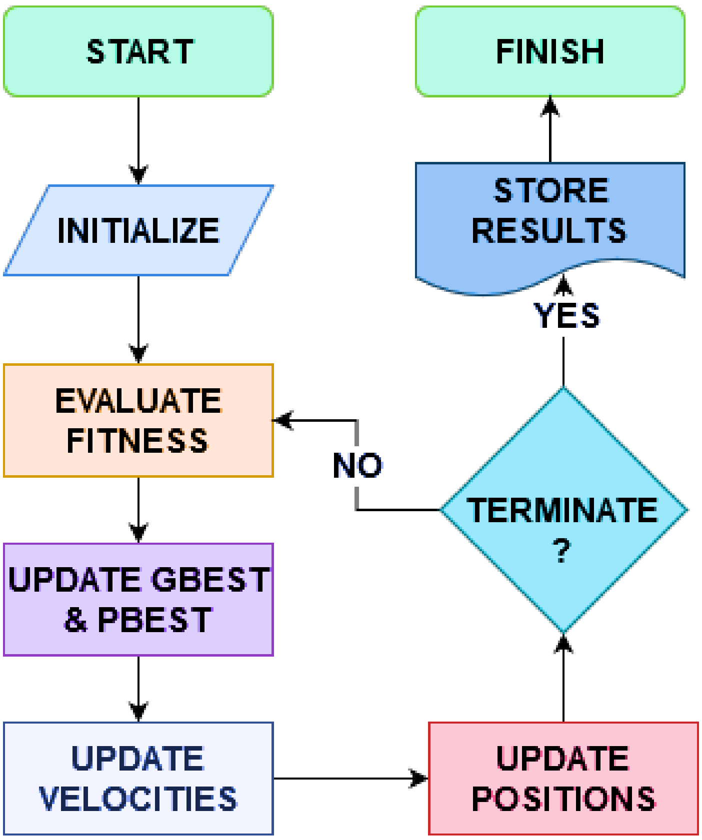


Fig. 3: Flowchart of the PSO algorithm.

Particle Swarm Optimization

PSO is a nature-inspired meta-heuristic optimization algorithm to solve the continuous nonlinear problems related to engineering. PSO is inspired by cognitive and social behaviours of the flock of birds or school of fish that are the swarm of animals hunt for food. PSO is a computationally efficient algorithm since its mathematical operators are primitive [30].

The individuals of the population are called *particle*. Particles are described as collision-proof birds in the initial formulation [34]. PSO algorithm performs the search for the solution through the particles whose trajectories are updated by both stochastic and deterministic rules. Every particle inside the swarm is influenced by the p_{best} and g_{best} in its random walk, where p_{best} is the personal best position of the particle and g_{best} is the global best position of the swarm [38]. Position and velocity update equations of particles are given in Eqs. (22-23).

$$v_{k+1} = w * v_k + c_1 * u_1 * (p_{\text{best}} - x_k) + c_2 * u_2 * (g_{\text{best}} - x_k) \quad (22)$$

$$x_{k+1} = x_k + v_{k+1} \quad (23)$$

where v is the velocity of the particle, w is the inertia weight, u_1 and u_2 are uniform distributed numbers between [0 1], c_1 is the coefficient of cognitive behaviour, c_2 is the coefficient of social behaviour, x is the position and lastly, subscript k is indexes of generations, respectively.

The flowchart of the PSO algorithm is given in Figure 3. Algorithm starts with initialization of the parameters and continues with fitness function evaluation. According to the fitness values of the particles, p_{best} and g_{best} are updated. Then, velocity and positions are calculated according to Eqs. (22-23). Algorithm continues until the pre-defined conditions are satisfied. Then, solutions are returned and algorithm ends.

Artificial Bee Colony

ABC algorithm can be considered as an extension to the bee swarm algorithm that uses the foraging behaviour. Leading modes of the algorithm are recruitment to a nectar source and abandonment of a source. Bees in the swarm are separated by their expertise areas such as onlooker bees, employed foragers, and scouts. Food source depends on many factors including distance to the nest, richness of source, and ease of extracting this energy [29]. Scout bees exhibit a random exploration search. Onlooker bees wait in the nest to gather information from the employed bees. Each onlooker bee then selects an appropriate food source depending on the calculated probability. The calculated probability mimics the *waggle dance* of the real bees performed by employed foragers. The more amount of nectar leads to longer dance duration [39]. Search process of the employed bees are same with the onlooker bees. Each employed bee maintains a unique nectar source [40].

The flowchart of the ABC algorithm is given in Figure 4. At first, initial bee swarm is randomly produced in the feasible search space. Bees are sent for food source exploration. After initial searching, employed foragers share the gathered information with the onlooker bees in the nest. Then, onlooker bees choose an appropriate food source depend on the following probability given in Eq. (24).

$$p_i = \frac{f_i}{\sum_{j=1}^{SN} f_j} \tag{24}$$

where p is the calculated probability with subscript i denotes the ith. food source, f is the value of the objective function, SN is the size of the swarm. The modification of the position of the bees to explore better food sources is given in Eq. (25).

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \tag{25}$$

where $-1 \leq \phi_{ij} \leq 1$ is a random number, v_{ij} is the recent generated position, x_{ij} is previous solution, $k \in \{1,2,\dots,E\}$ where E is the number of employed bees, respectively. After memorizing the best food source algorithm terminates if the predefined conditions are met. Best solution is returned and lastly algorithm ends.

4. PID Controller

PID controllers are one of the most preferred controllers in the areas of process control, motion control, hydraulics, pneumatics thanks to their simplicity, low maintenance costs and ease of implementation [41]. PID controllers deliver a good efficiency in terms of cost per benefit ratio where other controllers may fail [42]. Usage area of the PID controllers are not limited with just low–level control applications but PID controller are also employed in modern applications such as self–driving cars, autonomous robots, and UAVs [43].

PID controllers have three distinct terms as Proportional, Integral and Derivative that each term has one coefficient to adjust the performance and specifications of the controller. In the classical parallel form of the PID structure, time domain formula is given as follows.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{26}$$

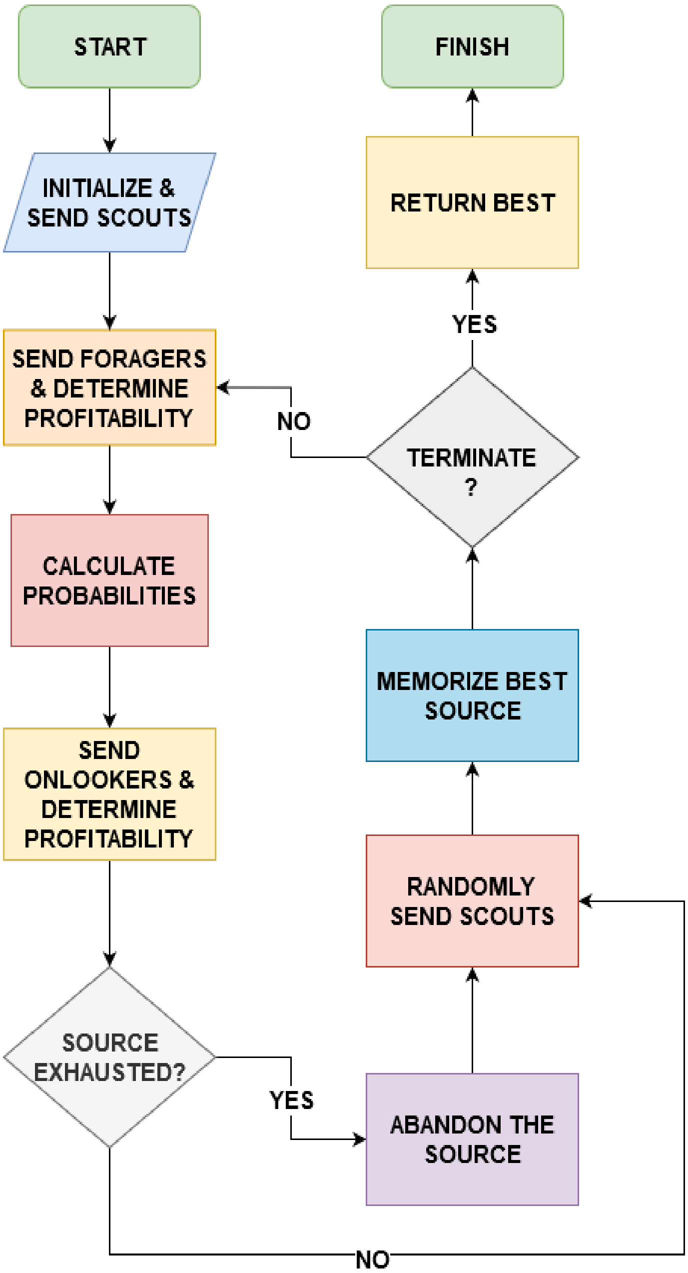


Fig. 4: Flowchart of the ABC algorithm

where $u(t)$ is input of the system, $e(t)$ is the error between the reference and feedback, K_p is the coefficient of proportional term, K_i is the coefficient of integral term and lastly K_d is the coefficient of derivative term, respectively. A block diagram representation of the classical PID controller scheme is given in Figure 5.

In the Figure 5, $x_{ref}(t)$ denotes the reference signal, $\tilde{x}$ denotes the measured signal, $e(t)$ is the difference between the observation and reference signals, $K_p e(t)$ is the proportional term, $K_i \int_0^t e(t)dt$ is the integral term, $K_d \frac{de(t)}{dt}$ is the derivative term, $u(t)$ is the input of the system, and $y(t)$ is the output of the plant dynamics, respectively.

The individual effects of PID terms can be given as follows [1].

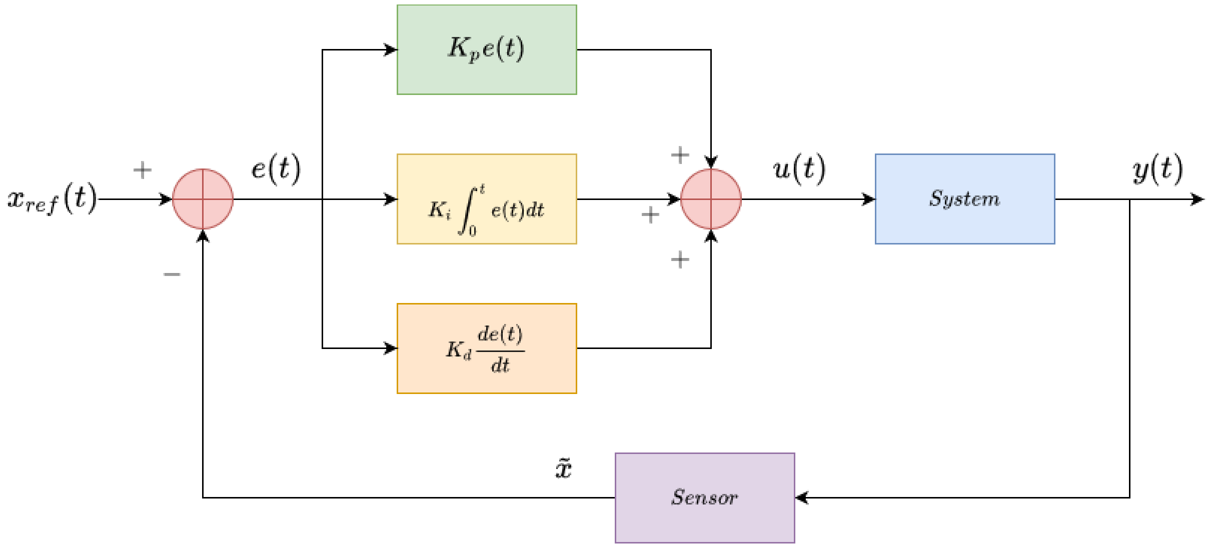


Fig. 5: Block diagram representation of the classical PID control scheme

- P provides an overall control action proportional to the error,
- I reduces the steady-state error by low-frequency compensation,
- D improves the transient response by high - frequency compensation, respectively.

Although K_p, K_i, K_d are mutually dependent in tuning, their individual closed-loop performance effects can be described in Table 1.

Table 1: Independent effects of K_p, K_i, K_d. Source: [1]

Closed-loop response	t_r	%	t_s	e_{ss}	*Stability*
K_p ↑ (increasing)	D ↓	I ↑	SI −↑	D ↓	Dg ↓
K_i ↑ (increasing)	SD −↓	I ↑	I ↑	LD ↓↓	Dg ↓
K_d ↑ (increasing)	SD −↓	D ↓	D ↓	MC −	Im ↑

where t_r is rise time, t_s is settling time, % is overshoot, e_{ss} is steady - state error, D is decrease, SD is small decrease, I is increase, SI is small increase, LD is large decrease, MC is minor change, Dg is degrade and lastly Im is improve.

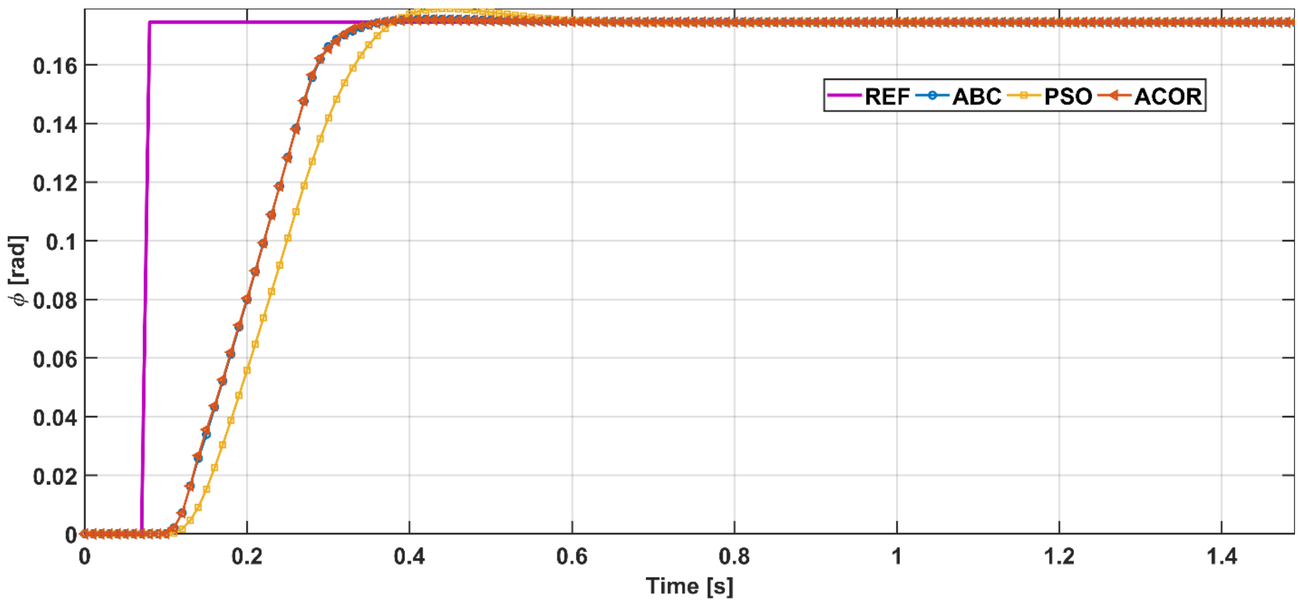
5. Results and Discussion

In order to assess the performance and efficiencies of the proposed methods, transient response analysis is conducted. Reference trajectories for the attitude angles are set as $\frac{\pi}{18}$ $[rad]$. Simulation time is 1.5 [s] with time step of 0.01 [s], respectively. Parameters of transient response analysis are rise time t_r, settling time t_s, maximum percentage overshoot $\%p$ and steady-state error e_{ss}. Rise time is the time duration that the response of the controller to rise from 10% to 90%. Settling time is the time duration that the error between the proposed controllers and the final reference value falls within the 2% of the final reference. Maximum percentage overshoot, as the name suggests, is the ratio of the overshoot with respect to final reference value. Steady-state error is the difference between the final value of the controller and the final value of the reference trajectory. Rise time and settling time are in [s], steady-state error is in [rad] and overshoot is given as [%].

The comparison results of the swarm intelligence based PID attitude controllers are given in Table 2 where boldfaces show the best response. According to the Table 2., it is seen that all the algorithms achieved 0 steady-state error, which shows that all the swarm intelligence based PID controllers can control the attitude states. However, there are some differences among the methods. For ϕ angle, ACO algorithm is the best compared to ABC and PSO with a rise time of 0.15 [s], settling time of 0.32 [s], and maximum percentage of 0.5%. For θ angle, both the ABC and ACO algorithms perform well and better than the PSO algorithm. While rise time of the ABC is the best, settling time and percentage overshoot of the ACO is better than the others. Lastly, for ψ angle, PSO algorithm has the best rise time and settling time responses. However, PSO has percentage overshoot of 0.06% while others have 0% overshoot.

Figures 6-8 show the attitude responses of the proposed controllers for ϕ, θ and ψ angles, respectively. According to the Figure 6 and 7, both the ACO and ABC algorithms perform similar and better than the PSO since PSO algorithm has overshoot and higher rise time characteristics for the given ϕ and θ trajectories. According to the Figure 8, PSO algorithm exhibits better convergence characteristics regarding ABC and ACO with a negligible amount of overshoot.

The algorithms are repeated for 30 MC trials to define the performance of the stochastic behavior of the swarm intelligence based methods. Also, maximum iteration of the meta-heuristics is set as 30, too. The fitness function of the swarm based meta-heuristics is given in Eq. (27).



. **Fig. 6:** Phi Response

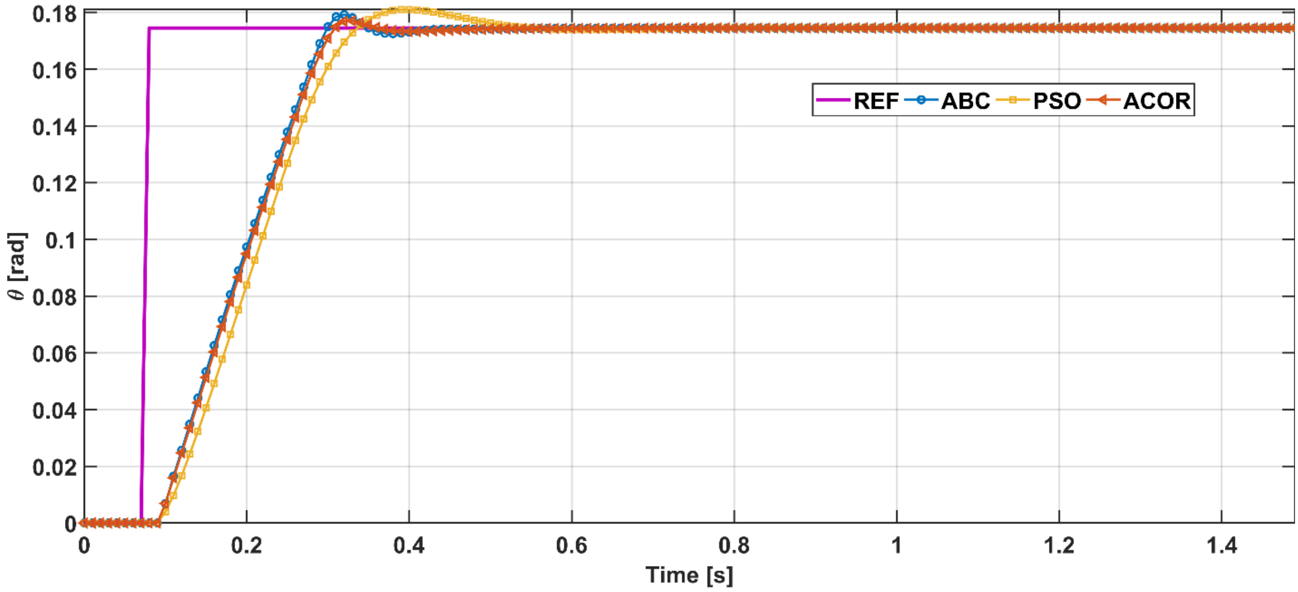


Fig. 7: Theta Response.

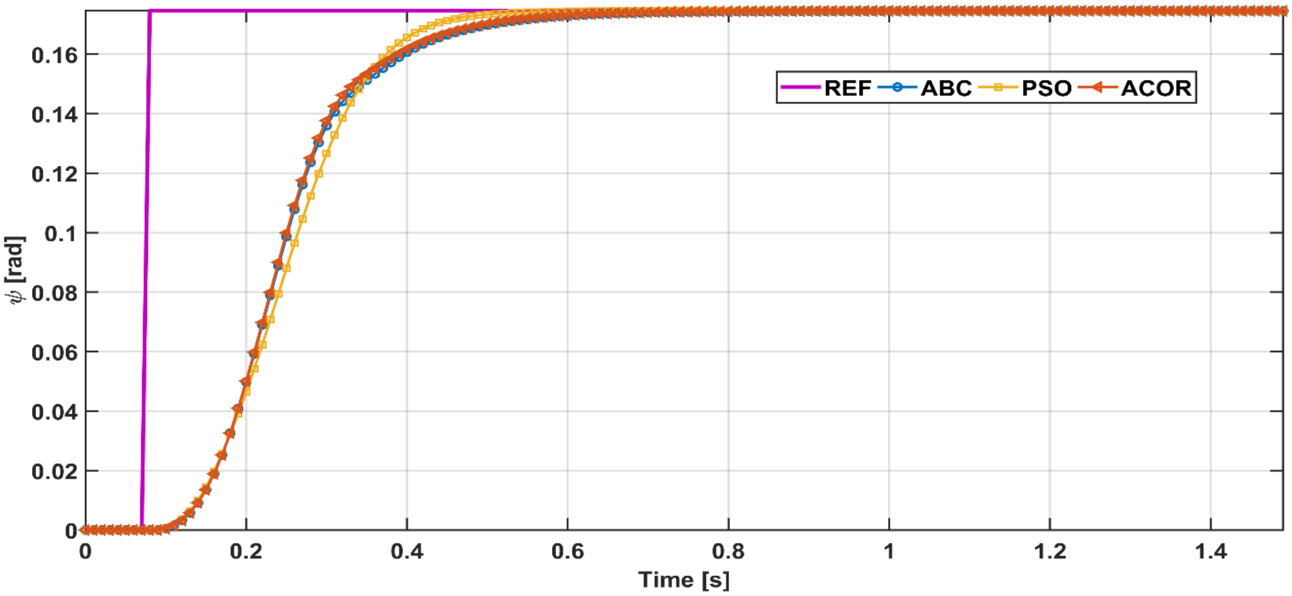


Fig. 8: Psi Response.

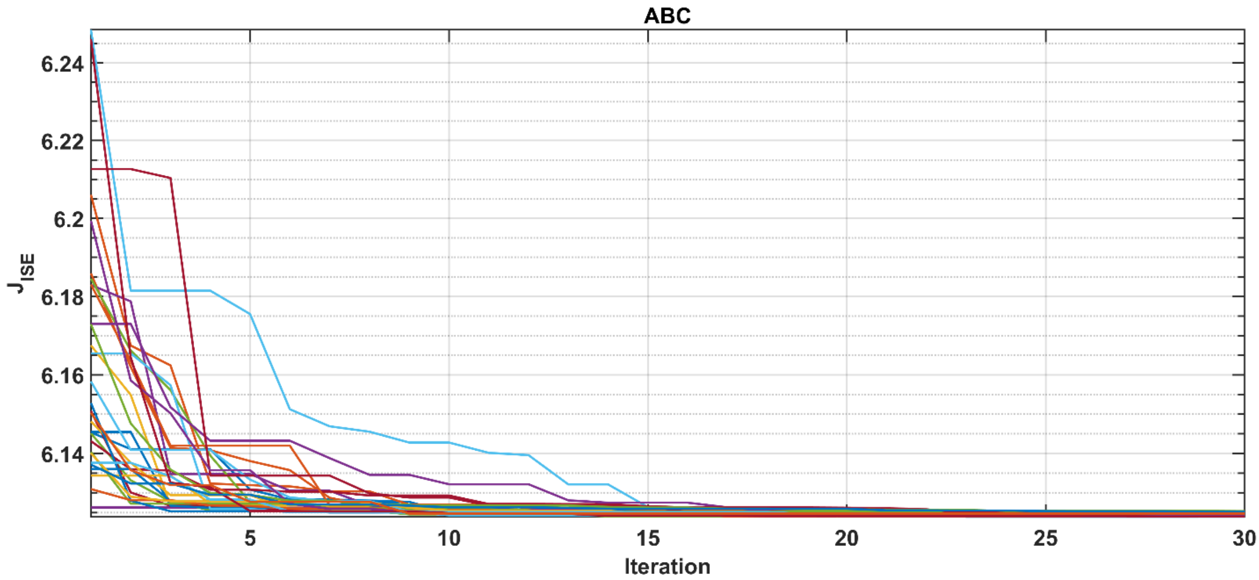


Fig. 9: MC analysis of the ABC algorithm

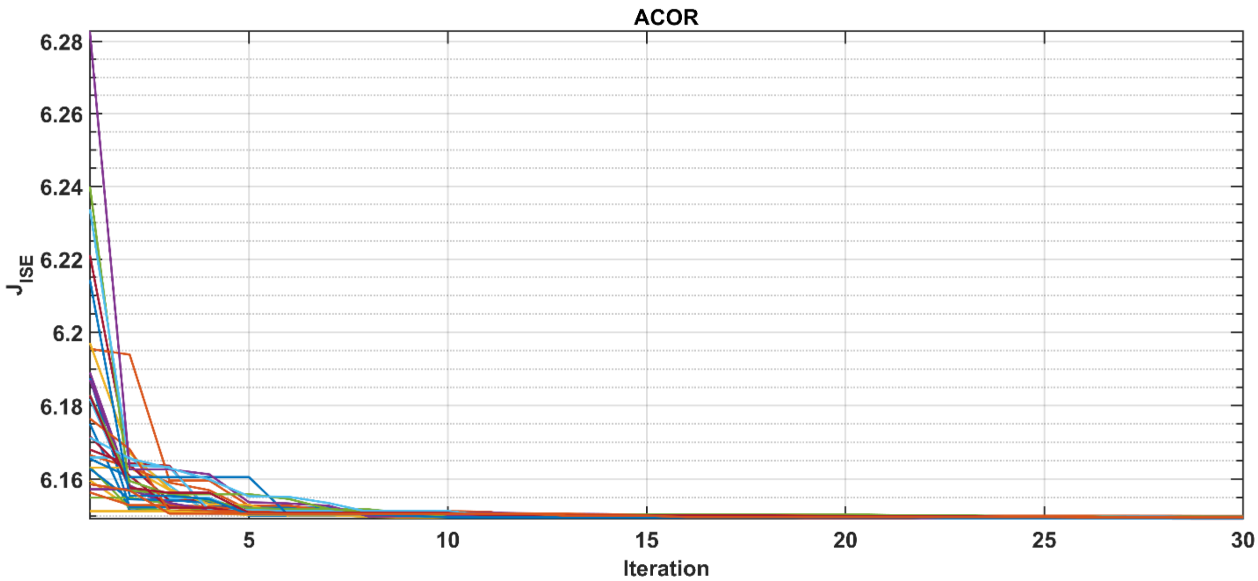


Fig. 10: MC analysis of the ACOR algorithm.

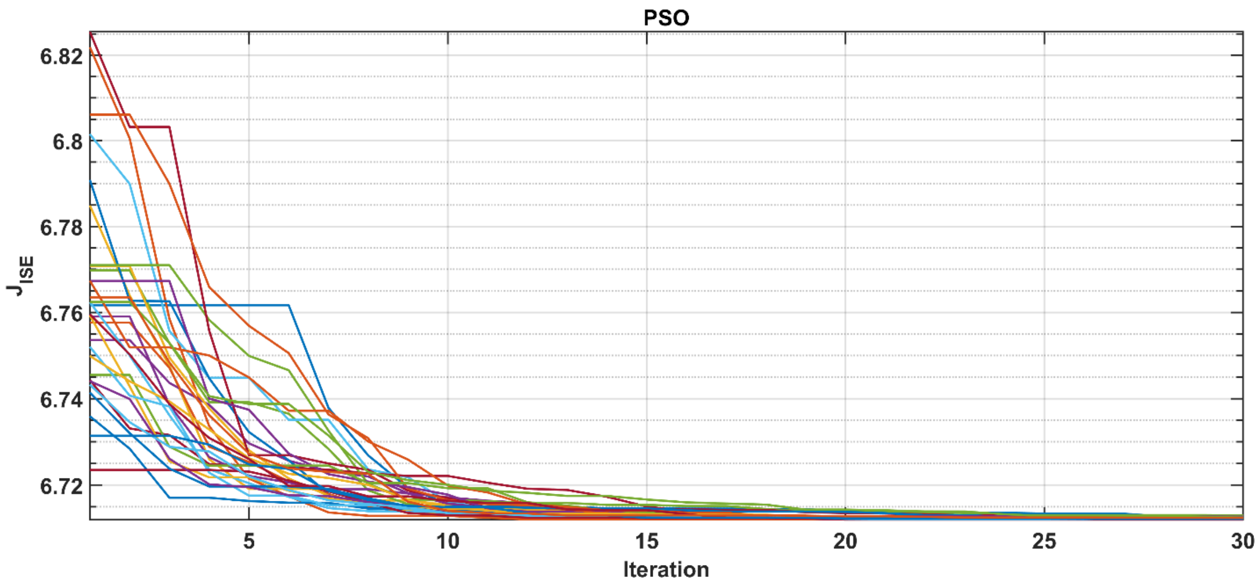


Fig. 11: MC analysis of the PSO algorithm.

Table 2: Transient response analysis of the proposed controllers

		ABC	ACO	PSO
ϕ	t_r	0.1511	0.1498	0.1733
	t_s	0.3260	0.3233	0.4977
	e_{ss}	0.0000	0.0000	0.0000
	%	0.6215	0.4965	2.6892
θ	t_r	0.1632	0.1662	0.1720
	t_s	0.3307	0.3002	0.4671
	e_{ss}	0.0000	0.0000	0.0000
	%	2.7012	1.4619	3.7248
ψ	t_r	0.2222	0.2140	0.2084
	t_s	0.5293	0.5198	0.4467
	e_{ss}	0.0000	0.0000	0.0000
	%	0.0000	0.0000	0.0604

$$J = \int_{t_1}^{t_2} e^2\, dt \quad (27)$$

where J is the fitness function, e^2 is the square of the error, t_1 and t_2 are the time limits of sampling frequency. J function is also known as ISE metric: integral squared error. Performances of the swarm intelligence methods for 30 MC run regarding iterations are given in Figures 9 to 11 for ABC, ACO and PSO, respectively. According to the figures, all the 30 MC runs of the ACO algorithm are converged to the sub–optimal region in first 10 iterations of the algorithm. The lowest fitness value of the ACO algorithm is 6.15. Convergence of the ABC algorithm to a sub–optimal point is around first 15 iterations. However, the lowest fitness value of the ABC algorithm is better than the others. MC results of the PSO algorithm are worse than that of both ABC and ACO, respectively.

6 Conclusion

In this work, a comparison of PID controllers based on swarm intelligence methods is conducted for attitude control problem of the nonlinear QUAV dynamics. Three well–known meta-heuristics (ABC, ACO and PSO) are implemented to tune the gains of the attitude controllers. ISE metric is employed as the fitness function. Transient analysis covering rise time, settling time, percentage overshoot and steady–state error is conducted. Also, convergence study of the proposed swarm algorithms based on MC is analysed.

According to the results, all the algorithms have achieved to control and track the given reference attitude trajectories with 0 steady–state error. However, ACO has better characteristics than the others in terms of transient response. MC analysis showed that all the meta-heuristic based methods have good convergence rate into the sub–optimal solution space within 15 iterations for 30 MC runs. So, the proposed controllers can optimize, control and track the pre-determined attitude trajectories within the limited time frame.

The future directions for the manuscript would cover both the employment of novel meta-heuristic algorithms and also the expansion of the full quadrotor states.

Nomenclature

ABC	: Artificial Bee Colony
ACO	: Ant Colony Optimization
B	: Body – fixed frame
BP	: Back Propagation
DC	: Direct Current
DE	: Differential Evolution
E	: Earth – fixed frame
DOF	: Degree – of - freedom
FPGA	: Field Programmable Gate Array
GA	: Genetic Algorithm
ISE	: Integral Squared Error
KF	: Kalman Filter
NN	: Neural Network
MC	: Monte Carlo
MIMO	: Multi Input - Multi Output
P	: Proportional Controller
PI	: Proportional Integral Controller
PD	: Proportional Derivative Controller
PID	: Proportional Integral Derivative Controller
PSO	: Particle Swarm Optimization
RBF	: Radial Basis Function
RPM	: Rotation per minute
TSP	: Traveling Salesman Problem
QUAV	: Quadrotor Unmanned Aerial Vehicle
UAV	: Unmanned Aerial Vehicle
VTOL	: Vertical Take – Off and Landing
ZN	: Ziegler – Nichols

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