# EMERGING 2023

The Fifteenth International Conference on Emerging Networks and Systems Intelligence

ISBN: 978-1-68558-110-7

September 25 - 29, 2023

Porto, Portugal

**EMERGING 2023 Editors**

Anders Fongen, Norwegian Defence University College, Norge

# EMERGING 2023

## Forward

The Fifteenth International Conference on Emerging Networks and Systems Intelligence (EMERGING 2023), held between September 25th and September 29th, 2023, continued a series of international events to present and evaluate the advances in emerging solutions for next-generation architectures, devices, and communications protocols. Particular focus was aimed at optimization, quality, discovery, protection, and user profile requirements supported by special approaches such as network coding, configurable protocols, context-aware optimization, ambient systems, anomaly discovery, and adaptive mechanisms.

Next generation large distributed networks and systems require substantial reconsideration of exiting ‘de facto’ approaches and mechanisms to sustain an increasing demand on speed, scale, bandwidth, topology and flow changes, user complex behavior, security threats, and service and user ubiquity. As a result, growing research and industrial forces are focusing on new approaches for advanced communications considering new devices and protocols, advanced discovery mechanisms, and programmability techniques to express, measure and control the service quality, security, environmental and user requirements.

We take here the opportunity to warmly thank all the members of the EMERGING 2023 technical program committee, as well as all the reviewers. The creation of such a high-quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to EMERGING 2023. We truly believe that, thanks to all these efforts, the final conference program consisted of top-quality contributions. We also thank the members of the EMERGING 2023 organizing committee for their help in handling the logistics of this event.

We hope that EMERGING 2023 was a successful international forum for the exchange of ideas and results between academia and industry and for the promotion of progress in the field of emerging networks and systems intelligence.

**EMERGING 2023 Chairs**

**EMERGING 2023 Steering Committee**
Euthimios (Thimios) Panagos, Perspecta Labs, USA
Raj Jain, Washington University in St. Louis, USA
Dimitris Kanellopoulos, University of Patras, Greece
Robert Bestak, Czech Technical University in Prague, Czech Republic
Jason Zurawski, Lawrence Berkeley National Laboratory / Energy Sciences Network (ESnet), USA
Emilio Insfran, Universitat Politècnica de València, Spain
Linda R. Elliott, Army Research Laboratory, USA

**EMERGING 2023 Publicity Chairs**
Laura Garcia, Universitat Politecnica de Valencia, Spain
Lorena Parra Boronat, Universitat Politecnica de Valencia, Spain

# EMERGING 2023
# Committee

## EMERGING 2023 Steering Committee

Euthimios (Thimios) Panagos, Perspecta Labs, USA
Raj Jain, Washington University in St. Louis, USA
Dimitris Kanellopoulos, University of Patras, Greece
Robert Bestak, Czech Technical University in Prague, Czech Republic
Jason Zurawski, Lawrence Berkeley National Laboratory / Energy Sciences Network (ESnet), USA
Emilio Insfran, Universitat Politècnica de València, Spain
Linda R. Elliott, Army Research Laboratory, USA

## EMERGING 2023 Publicity Chairs

Laura Garcia, Universitat Politecnica de Valencia, Spain
Lorena Parra Boronat, Universitat Politecnica de Valencia, Spain

## EMERGING 2023 Technical Program Committee

Andrea F. Abate, University of Salerno, Italy
Dorel Aiordachioaie, Dunarea de Jos University of Galati, Romania
Mohammed GH. AL Zamil, Yarmouk University, Jordan
Firkhan Ali Bin Hamid Ali, Universiti Tun Hussein Onn Malaysia, Malaysia
Nik Bessis, Edge Hill University, UK
Robert Bestak, Czech Technical University in Prague, Czech Republic
Adil Bilal, University of Canterbury, New Zealand
Tetiana Biloborodova, G.E. Pukhov Institute for Modelling in Energy Engineering - National Academy of Sciences of Ukraine, Kyiv, Ukraine
Lucas Botoni de Souza, Federal University of Technology - Paraná, Brazil
Graziana Cavone, Polytechnic of Bari, Italy
Chin-Chen Chang, Feng Chia University, Taiwan
Hyung Jae (Chris) Chang, Troy University, USA
Hongxu Chen, University of Technology, Sydney
Arun Das, Visa Inc., USA
David de Andrés, Universitat Politècnica de València, Spain
Renato De Leone, University of Camerino, Italy
Ramadan Elaiess, University of Benghazi, Libya
Linda R. Elliott, Army Research Laboratory, USA
Stefka Fidanova, Institute of Information and Communication Technologies - Bulgarian Academy of Sciences, Bulgaria
Nuno Gonçalves Rodrigues, Polytechnic Institute of Bragança, Portugal
Chunhui Guo, San Diego State University, USA
Ridewaan Hanslo, University of Pretoria, South Africa
Mohd Helmy Abd Wahab, Universiti Tun Hussein Onn Malaysia, Malaysia
Sergio Ilarri, University of Zaragoza, Spain
Oleg Illiashenko, National Aerospace University "KhAI", Ukraine

Emilio Insfran, Universitat Politecnica de Valencia, Spain
Raj Jain, Washington University in St. Louis, USA
Jin-Hwan Jeong, SK telecom, Republic of Korea
Dimitris Kanellopoulos, University of Patras, Greece
Ah-Lian Kor, LeedsBeckettUniversity, UK
Igor Kotsiuba, PIMEE NAS of Ukraine, Ukraine
Marcos Levano, Catholic University of Temuco, Chile
Vitaly Levashenko, University of Zilina, Slovakia
Keqian Li, Yahoo Research, USA
Yanjun Liu, Feng Chia University, Taiwan
Zoubir Mammeri, IRIT - Paul Sabatier University, Toulouse, France
Christopher Mansour, Mercyhurst University, USA
Nada Matta, University of Technology of Troyes, France
Andrea Michienzi, University of Pisa, Italy
Nader Mir, San Jose State University, USA
Ioannis Moscholios, University of Peloponnese, Greece
Giovanni Nardini, University of Pisa, Italy
Chika Oshima, Saga University, Japan
Euthimios (Thimios) Panagos, Perspecta Labs, USA
Isidoros Perikos, University of Patras, Greece
Przemyslaw (Przemek) Pochec, University of New Brunswick, Canada
Chuan Qin, University of Shanghai for Science and Technology, China
Danda B. Rawat, Howard University, USA
Muhammad Hassan Raza, Dalhousie University, Halifax, Canada
Federica Rollo, University of Modena and Reggio Emilia, Italy
Davide Rua Carneiro, School of Management and Technology - Polytechnic of Porto, Portugal
Francesco Rundo, STMicroelectronics Srl - ADG Central R&D, Italy
Khair Eddin Sabri, The University of Jordan, Jordan
Christian Schulz, Heidelberg University, Germany
Ivan Serina, University of Brescia, Italy
Hirokazu Shimauchi, Hachinohe Institute of Technology, Japan
Masakazu Soshi, Hiroshima City University, Japan
Olarik Surinta, Mahasarakham University, Thailand
Bashir Tenuche, Kogi State University, Anyigba, Nigeria
Hui Tian, National Huaqiao University, China
Joseph G. Vella, University of Malta, Malta
Antonio Virdis, University of Pisa, Italy
Wuyi Yue, Konan University, Japan
Daqing Yun, Harrisburg University, USA
Elena Zaitseva, University of Zilina, Slovakia
Jie Zhang, Amazon AWS, USA
Minfan Zhang, Aviva, Canada
Sotirios Ziavras, New Jersey Institute of Technology, USA
Jason Zurawski, Lawrence Berkeley National Laboratory / Energy Sciences Network (ESnet), USA

## Copyright Information

For your reference, this is the text governing the copyright release for material published by IARIA.

The copyright release is a transfer of publication rights, which allows IARIA and its partners to drive the dissemination of the published material. This allows IARIA to give articles increased visibility via distribution, inclusion in libraries, and arrangements for submission to indexes.

I, the undersigned, declare that the article is original, and that I represent the authors of this article in the copyright release matters. If this work has been done as work-for-hire, I have obtained all necessary clearances to execute a copyright release. I hereby irrevocably transfer exclusive copyright for this material to IARIA. I give IARIA permission or reproduce the work in any media format such as, but not limited to, print, digital, or electronic. I give IARIA permission to distribute the materials without restriction to any institutions or individuals. I give IARIA permission to submit the work for inclusion in article repositories as IARIA sees fit.

I, the undersigned, declare that to the best of my knowledge, the article is does not contain libelous or otherwise unlawful contents or invading the right of privacy or infringing on a proprietary right.

Following the copyright release, any circulated version of the article must bear the copyright notice and any header and footer information that IARIA applies to the published article.

IARIA grants royalty-free permission to the authors to disseminate the work, under the above provisions, for any academic, commercial, or industrial use. IARIA grants royalty-free permission to any individuals or institutions to make the article available electronically, online, or in print.

IARIA acknowledges that rights to any algorithm, process, procedure, apparatus, or articles of manufacture remain with the authors and their employers.

I, the undersigned, understand that IARIA will not be liable, in contract, tort (including, without limitation, negligence), pre-contract or other representations (other than fraudulent misrepresentations) or otherwise in connection with the publication of my work.

Exception to the above is made for work-for-hire performed while employed by the government. In that case, copyright to the material remains with the said government. The rightful owners (authors and government entity) grant unlimited and unrestricted permission to IARIA, IARIA's contractors, and IARIA's partners to further distribute the work.

## Table of Contents

# Data Sharing Services in a Space Information Network

Anders Fongen
Norwegian Defence University College (FHS)
Lillehammer, Norway
email: anders@fongen.no

***Abstract*—For collaboration services in a Space Information Network, services and data structures for sharing are essential. The organization and placement of resources for that purpose must consider the semantics of the sharing operations, like discovery, transactional properties, update ordering, and update notification. These aspects are analyzed and discussed in the manuscript, and the more realistic sharing mechanisms are also evaluated through simulation experiments.**

***Keywords*—*LEO satellites; space information networks; data sharing; mobile computing.***

## I. INTRODUCTION

The term *Space Information Network* (SIN) describes a set of satellites that cooperatively offer services for information processing and sharing, as well as traditional communication services. SIN is regarded as a natural evolution of satellite services, from radio mirrors in geostationary orbit to Low Earth Orbit (LEO) constellation for communication services (e.g., Iridium) [1][2].

In a series of previous publications, different aspects of SIN operation (architecture [3], security [4], cache management [5], routing [6], and state management [7]) have been addressed. This article will focus on the design of data sharing mechanisms, their semantics, resource placement and optimization.

For the sake of successful collaboration services in a SIN, data sharing mechanisms are strictly necessary, and should not be left to ground-based services. An important advantage of a SIN is the potential for very low latency, which is best maintained by a sharing service offered by the satellite network itself.

Application clients on the surface, denoted $C_a$, will connect to any satellite overhead, which serves as an *application server*, $S_a$. When in need for access to shared data, $S_a$ will communicate with the sharing instance $S_s$. Three tiers are thus involved, and $C_a$ will never make direct contact with $S_s$. Please observe that while the $C_a$ to $S_a$ connection is a *link*, the $S_a$ to $S_s$ connection can have multiple hops. These relations are illustrated in Figure 1.

Data sharing in a SIN will benefit from the predictable properties of a satellite network. The position of every satellite can be computed by anyone at any time, as well as inter-satellite link availability and the population density inside a satellite's footprint. These properties alleviate the need for a discovery service and allow the resource management to anticipate the periods of high and low traffic intensity from surface clients.

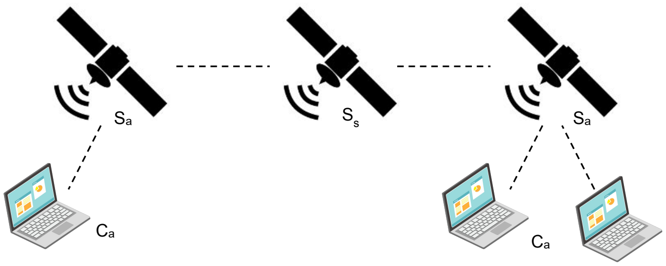


Figure 1. The relation between the application clients ($C_a$), application servers ($S_a$) and shared data servers ($S_s$).

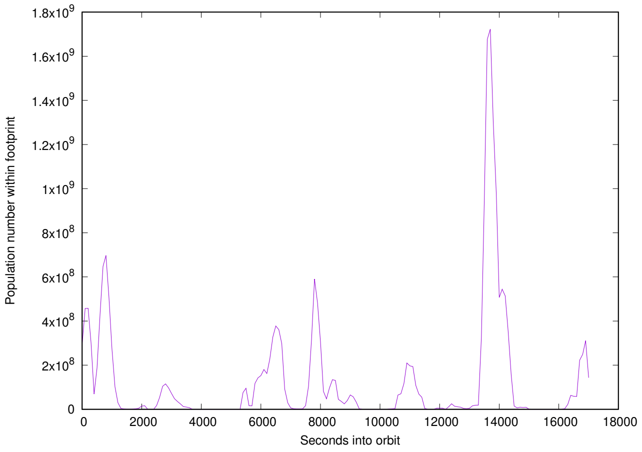


Figure 2. The population number inside the footprint of a satellite during three subsequent orbits.

The population distribution of the planet is highly uneven. A satellite (serving the $S_a$ role) in orbit will expect great variations in the workload offered by $C_a$: short-termed peaks of high traffic intensity between longer periods of little activity. Figure 2 shows the population density variations during three orbits at 500 km altitude. This property represents a scalability problem on one hand, and an opportunity for improved resource planning on the other.

Another property of any LEO network is the need for frequent handover of $C_a$ to $S_a$ link, including migration of those resources on which $C_a$ depends. Session state and service endpoints need to shift to other $S_a$ in order to maintain the communication to the $C_a$ [7].

The perspective of the presented analysis is that from Distributed Computing. Technical and physical properties of satellites related to energy management, antenna design, modulation, coding, jamming resistance etc., are not taken into consideration.

In the analysis following in this paper, the assumption is made that the access operation from $S_a$ to the data elements in $S_s$ is *not* uniformly distributed. The access frequency follows a *Scale Free Distribution* model (SFD), in which the access frequency of an element is inversely proportional to it *rank*.

The remainder of the paper is organized as follows: Section II will discuss typical and essential properties of a sharing service, and Section III will briefly present the software simulation model used in the experiments. Alternative methods for migration of shared data during handover operations are discussed in Section IV, while an optimization experiment for placement of a shared service is presented in Section V. Experimental results regarding path cost for connections are presented in Section VI. Finally, the paper lists its conclusions in Section VII.

## II. DATA SHARING SEMANTICS

Operations on data elements in $S_s$ involve critical regions which must be protected to avoid race conditions and update conflicts. Furthermore, there are semantic properties related to access and update operations which should be considered for implementation:

*a) Transactional atomicity and isolation:* Assumed implemented in the traditional ACID way. If used correctly, it protects the data element against update conflicts. It requires a network-wide mutex mechanism, which is a dangerous thing to use since $S_a$ can crash and restart any time.

*b) Ordering semantics:* Guarantees the observed ordering of updates received from other shared data collections. This is a well studied problem, discussed, e.g., in [8]. The so-called *causal ordering semantics* strikes a good balance between implementation complexity and usefulness to a range of communication patterns (through the use of, e.g., Lamport clocks [9]). Other ordering models, like the FIFO ordering and the less formal “eventual consistency” are easier to implement but also less useful.

*c) Update notification:* An event notification system whereby $S_a$ can listen for notifications from update operations on the $S_s$ allows for interesting application patterns. The *observer/observable* and the *model-view-controller* patterns are well known to any programmer, they allow multiple $S_a$ to obtain an (eventually) consistent view of the shared data without the need for continuous polling of its state.

*d) Relational data base:* A well known and mature organization of a data set expressed through relational algebra, with excellent support for transactional properties, security and redundancy. May well serve as a service endpoint in $S_s$, but does not lend itself well to frequent migration.

The sharing models listed above have different semantic properties, and varying ability to operate under the circumstances found in a SIN. An analysis of how well they may adapt to the *mobility properties*, $S_a$ *group dynamics*, etc., is presented in Sections II-A and II-B.

### A. Mobility properties

For a $C_a$, an $S_a$ will stay within line of sight for approximately 15 minutes (assuming a LEO satellite constellation) after which a handover operation needs to take place. A handover implies that all the resources necessary to uphold a continuous service must be migrated to the new satellite. In addition, resources referenced in other satellites will also move in the same fashion, and a handover of these resources may be necessary in order to maintain a short communication path.

The mobility pattern of satellites is completely predictable, which means that any two identified satellites can predict if they are within radio range of each other. Link discovery is not necessary, but the connecting part will need to learn the ID of the other satellite for this calculation to take place [6]. Once the initial connection has been established, it can be used to notify the peer of upcoming handover operations.

The handover operation for a $S_s$ may find it unnecessary to migrate all shared data elements to the next satellite, but will need to establish the service endpoint in the new satellite and notify all client $S_a$ about the new endpoints. Shared data elements may be left behind and fetched on-demand, which will be described in Section IV.

### B. Client group dynamics

Associated with an $S_s$ is a group of $S_a$ instances. The membership of this group is constantly changing as the $S_a$’s need for shared data access emerges and ends.

An $S_a$ will need to know where the needed $S_s$ is, also during and after a handover operation. If the $S_s$ need to send update notifications to the $S_a$, some form of group membership protocol must be in operation which will consume a portion of the communication capacity. A better arrangement for group membership handling will be presented in Section VI.

### C. Shared memory or service interface

Two possible methods for $S_a$ access to $S_s$ are (1) *shared memory* or (2) *service interface*. Method (1) allows $S_a$ to access shared data like memory cells in the computer, for either write or read. In order to protect read-test-write sequences from race conditions, distributed mutexes must be in place. A distributed mutex carries the risk for deadlocks in the case where $S_a$ crash with acquired mutexes. Also, the method is unable to offer any consistency, event notification or ordering guarantees.

The list of properties in this section strongly suggests a service oriented interface for the shared data in $S_s$. A service implementation allows both simple and composite operations to take place in a threadsafe, synchronized, protected and reliable manner. Event notifications can also be offered from a service interface, although long-termed (asynchronous) service invocations need to consider handovers and change of IP addresses during the invocation.

For the rest of this manuscript, $S_s$ access is assumed to be implemented through a service interface, not as direct access to memory cells.

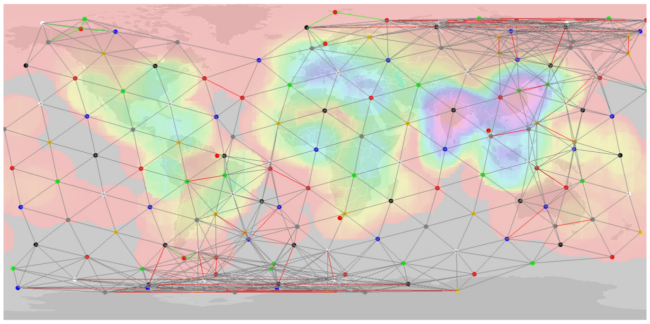


Figure 3. Screenshot from the satellite constellation model.

### D. Shared data access pattern

The shared data elements in $S_s$ are not likely to be accessed in a uniform manner, i.e., with the same access frequency, but more likely to be accessed according to a *Scale Free Distribution* model (SFD). The SFD predicts usage and access patterns for a range of human activities and natural phenomena [10]. In this particular use case, the data elements are *ranked* according to their access frequency. Assuming SFD, the relative frequency (f) of accesses to an element is expected to be inversely proportional to the rank (r) of that element. Applied to this use case, SFD predicts that the most frequently used element will be accessed twice as often as the second most frequently used element, three times more often than the third most frequently access element, and so on. Mathematically, this may be expressed as

$$f = \frac{a}{r} \tag{1}$$

where $a$ is given a value so that

$$\sum_{r} \frac{a}{r} = 1 \tag{2}$$

## III. The software model

The results presented in this article are based on a software simulation of a satellite constellation. A screenshot from the model is shown in Figure 3. The constellation consists of 150 satellites at 500 km altitude. The colored backdrop in the figure indicates the population density inside the satellite footprint at a given location, based on gridded population data from NASA [11]. This data set has also been used to calculate the graph in Figure 2.

## IV. Migration pattern for shared data

The actual location for $S_s$ needs to be established, and the most obvious method would be to store the shared data elements inside the satellite which offers the $S_s$ service interface. In this case, the entire data set will be migrated during a handover of the service interface.

The assumption was made in Section II-D that the pattern of access operations follows a *Scale Free Distribution* [10] which allows for a more scalable design: After a handover operation of the $S_s$ service interface, the shared data elements are not migrated until they are referenced by a call from a $S_a$. The elements which are never referenced during the following service period are then left behind by *two* hops at the next handover operation, etc. The elements that are never again referenced will therefore not consume any link capacity. Although applied for a different use case, the results obtained in [7] use similar mathematics and will be presented here as a simulated result for on-demand migration of shared data elements.

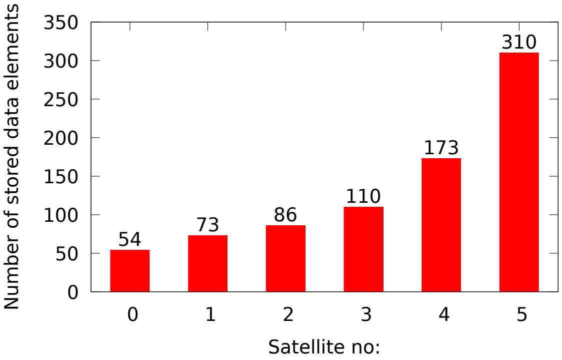


Figure 4. The distribution of shared data elements after 5 handover operations.

The distribution of shared data elements has been simulated with these parameters:

- 5 handover operations, involving 6 $S_s$ satellites
- 1000 $S_s$ accesses from $S_a$ to each satellite
- There are 1000 shared data elements in total
- Shared data elements are accessed according to SFD

The resulting distribution is shown in Figure 4. The sum of all numbers (806) shows that far from every shared data element were ever accessed, and existing elements remaining in storage of previous satellites indicate that they were never accessed since that satellite's time of service.

The number of link traversals used for migration of data elements during the course of the simulation is chosen as an indicator of the scalability properties of the arrangement. Therefore, the number of single hop movements of elements will be analysed under the scenario described in this section. The resulting numbers from the proactive and the on-demand migration method are compared and reported.

The distribution of the shared data elements across the current and past $S_s$ satellites was measured just before a handover operation, after 1000 access operations. The numbers are shown in Table I. From these numbers, it is possible to calculate the total number of element movements across inter-satellite links during the scenario of 5 handover operations with 1000 access operation between each.

For the proactive element migration method, the total number of link traversals is 2910 (the sum of the 5 first numbers in the "total" column). For the on-demand method, the total number is 1162. This means that the on-demand method consumes only 40 % of the communication capacity required by the proactive method.

TABLE I
DISTRIBUTION OF SHARED ELEMENTS ACROSS $S_s$ SATELLITES BEFORE EACH HANDOVER.

| satellite total | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 336 | 336 | | | | | |
| 499 | 172 | 327 | | | | |
| 608 | 118 | 168 | 322 | | | |
| 704 | 91 | 113 | 157 | 343 | | |
| 763 | 67 | 94 | 108 | 164 | 330 | |
| 806 | 54 | 73 | 86 | 110 | 173 | 310 |

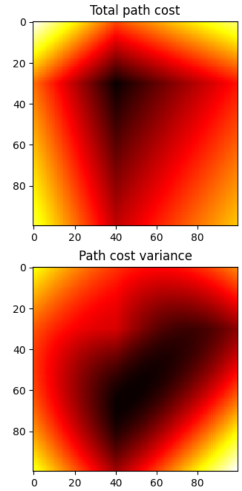


Figure 5. The distribution of total path cost and its variance for 5 $S_a$ inside a grid of 100x100 possible locations for the $S_s$.

## V. BEST PLACE FOR THE SHARING SERVICE

Given that there is a number of $S_a$ satellites in need of cooperation over a $S_s$ service, there is an optimal position for $S_s$ based on one or more criteria.

For client satellite $p$, the access frequency to the shared service is $f_p$ and the path length to the service is $d_p$. The chosen criteria are:

1) The total number of link traversals, i.e., $\sum d_i \cdot f_i$, should be minimized.
2) The network load offered by the clients should be evenly distributed, i.e., $\mathrm{Var}(d_i \cdot f_i)$ should be minimized.

A quick look into these criteria is shown in Figure 5 as a heat map. The black color represents the lowest number, white color the highest. The $S_a$ nodes are placed in each corner with access frequencies ($f_p$) 1,2,4 and 8, and a fifth client in position (30,40) and $f_p = 15$. Each pixel in the heat map represents a candidate placement for $S_s$ and the color the corresponding sum and variance for the path cost for $S_a$ to $S_s$ communication.

As shown in the heat map, the lowest total path cost is obtained with the $S_s$ located near the $S_a$ with highest $f_p$, in this case the client in position (30,40). The heat map also shows that this position does not give the lowest variation, which is found a little to the "south" of it.

## VI. CONNECTIVITY AND PATH LENGTH

Beside migration of shared data elements and optimal placement of the $S_s$, the conditions for the communication between the $S_a$ and the $S_s$ should be investigated.

Possible strategies for routing inside the satellite grid in a SIN have been studied in [6], where the hypothesis was that the forwarding path should aim to involve less busy satellites. Also important, the study showed that the grid is never partitioned, so one $S_a$ will always be able to communicate with a $S_s$, regardless of their positions. This property is also shown in Figure 3. The path cost for general routing shows a significant improvement with that approach, but also large fluctuations. There is consequently no need for a separate routing mechanism for shared data access, but a *discovery service* for $S_a$ to find the $S_s$ at the beginning of a session is needed. During a $S_s$ handover, the server can leave a "breadcrumb" which points to the new location, for the subsequent redirection of the $S_a$.

## VII. CONCLUSION

Any collaboration between a group of $C_a$ will require coordinated access to a body of shared data. This paper has investigated four aspects of a sharing mechanism: Service semantics, migration of shared data elements, placement of the shared service endpoint, and routing methods for communication between $S_a$ and $S_s$.

The optimization methods suggested during the course of the paper are based on the special properties of a SIN operation: Predictability and uneven population density.

This is a part of an ongoing feasibility study and there are still many details in need for a detailed study, which will be the focus for further research effort in the field of SIN operation.

## REFERENCES

[1] S. Briatore, N. Garzaniti, and A. Golkar, "Towards the internet for space: Bringing cloud computing to space systems," in *36th International Communications Satellite Systems Conference (ICSSC 2018)*, 2018, pp. 1–5.

[2] L. Bai, T. de Cola, Q. Yu, and W. Zhang, "Space information networks," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 8–9, 2019.

[3] A. Fongen, "Application services in space information networks," in *CYBER 2021*. Barcelona, Spain: IARIA, Oct 2021, pp. 113–117.

[4] A. Fongen, "Trust management in space information networks," in *SECURWARE 2021*. Athens, Greece: IARIA, Nov 2021, pp. 14–18.

[5] A. Fongen, "Cooperative caching in space information networks," in *INTERNET 2022*. Venice, Italy: IARIA, May 2022, pp. 1–5.

[6] A. Fongen, "Population-based routing in leo satellite networks," in *MOBILITY 2022*. Porto, Portugal: IARIA, June 2022, pp. 1–4.

[7] A. Fongen, "Transfer of session state between satellites in a space information network," in *INTERNET 2023*. Barcelona, Spain: IARIA, March 2023, pp. 1–4.

[8] A. S. Tanenbaum and M. van Steen, *Distributed Systems: Principles and Paradigms*, 2nd ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2007.

[9] L. Lamport, "Time, clocks, and the ordering of events in a distributed system." *Communications of the ACM*, vol. 21, no. 7, pp. 558–565, jul. 1978.

[10] A.-L. Barabasi, *Linked: How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life*. Plume Books, April 2003.

[11] "Gridded population of the world v.4.11," [Online; retrieved 15-Aug-2023]. [Online]. Available: https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse

# Lowering the Effects of Virtual Reality Cybersickness: A Systematic Review

Monique Hanslo
*University of South Africa*
Pretoria, South Africa
nickyhanslo@gmail.com

Ridewaan Hanslo
Department of Informatics
University of Pretoria
Pretoria, South Africa
ridewaan.hanslo@up.ac.za

***Abstract*—Virtual Reality (VR) has several uses in business, entertainment, and training. A simulation sickness known as 'cybersickness' is experienced when using VR. Cybersickness (CS) poses a severe obstacle to VR systems' usability. To fully utilize VR as a medium, it is essential to reduce the uncomfortable sensation of CS. Technology, software, and user attributes all play a role in creating a pleasant VR experience. There is no comprehensive information on what causes cybersickness, how the severity of cybersickness can be assessed, and what factors contribute to CS in a VR environment. Because of this gap, this research aims to unpack the causes of cybersickness, how to assess it, and to identify and describe the factors. A systematic literature review identified 21 factors contributing to VR CS. In addition, a conceptual model was developed to allow researchers and VR developers to evaluate these factors.**

***Keywords-virtual reality; simulation sickness; cybersickness; factors; head-mounted display; systematic review.***

## I. INTRODUCTION

VR has recently become part of everyday vocabulary, which can be partly ascribed to the recent media coverage it has received [1]. Simply put, VR offers a Virtual Environment (VE) that enables users to engage with a highly realistic artificial world made mostly of three-dimensional computer-generated images, audio, and haptic input. VR has been used in various fields, such as healthcare, construction, and architecture. Still, video games have drawn consumers' attention more than other VR applications [2]. The leading technology for virtual worlds is visual devices known as Head Mounted Displays (HMDs), which are very different from standard screens since they completely immerse the user in the VE by obstructing outside visual inputs that can interfere with the experience. A negative side effect known as Cybersickness (CS) has also been identified with such immersive experiences [2].

An unpleasant collection of symptoms called 'cybersickness' is brought on by being in a VE and can linger for a short while or even for days [3]. Examples of such symptoms include headache, nausea, and even vomiting [4]. According to estimates, CS affects 20% to 80% of the population in some way [3]. CS claims have been rising along with the popularity of VR gadgets, despite the fact that the ailment has long been understood and researched [2].

In the worst situations, the symptoms are so severe that people cannot utilize VR equipment. In one instance, game makers were forced to remove VR components from their creations because users complained of feeling unwell [2]. The symptoms of CS may interfere with medical therapy and have unfavourable repercussions on the patient. Even minor symptoms might be unpleasant and bother the user.

### A. Problem Statement

VR gives people a chance to imagine a modified three-dimensional world. However, for optimal efficiency, it necessitates total sensory awareness. Interactions and visual signals in the VE must be effectively developed to be as realistic as possible before VR is adequately adapted and understood [4]. Its effectiveness can be measured by how much the user feels immersed in the surroundings [5]. Usability problems, such as the symptoms related to CS, will reduce the feeling of presence in a VE. If users have trouble using the environment, they won't be able to experience the reality of a VE.

Numerous factors lead to CS, and the knowledge base needs a comprehensive view of all that can lead to it. Because of this research gap, this study aims first to identify the factors contributing to CS during VR technology use. Secondly, a conceptual model will be created incorporating these identified factors.

### B. Research Objectives

The following are the objectives of this study:

1) *To determine the causes of Cybersickness in the Virtual Reality environment.*
2) *To determine the severity of cybersickness experienced, or susceptibility to it, before, during, or following a Virtual Reality session?*
3) *To determine the factors that contribute to Virtual Reality Cybersickness*

### C. Research Questions

This research will address the following research questions:

1) *What are the causes of cybersickness in the Virtual Reality environment?*
2) *How can the severity of cybersickness experienced, or susceptibility to it be assessed before, during, or following a VR session?*
3) *Which factors contribute to Cybersickness during the application of Virtual Reality technologies?*

### D. Significance of the Study

This study aims to present a holistic view of all the factors that are posited to cause CS in a VR environment. It seeks to provide current and forthcoming VR developers with helpful guidance on reducing CS symptoms to facilitate a good VR experience. It will also act as a source of information for researchers delving into CS in VR. This will serve as a roadmap for expanding the study and making the link to the variables employed. Additionally, it is believed that this research can aid users who experience CS in VR settings by enhancing their user experience.

The rest of this paper is organized as follows. Section II provides literature on cybersickness causes and theories, and the measurement methods deployed. Section III presents the research methodology to conduct the Systematic Literature Review (SLR). The results of the SLR are presented in Section IV and a discussion of the research findings are provided in Section V. Section VI concludes the paper and provides recommendations for future research.

## II. LITERATURE REVIEW

### A. *Cybersickness Causes and Theories*

#### 1) *Sensory Conflict Theory*

CS is a disorder that is difficult to categorize since there are a variety of symptoms, the illness's effects differ from person to person, and there are many theories as to how it began [3][33]. The hypothesis discussed the most in literature is the Sensory Conflict Theory (SCT). It contends that CS results from a conflict between the information provided by several senses. It has been demonstrated that common motion sickness signs and physiological modifications, such as car or seasickness, are relatively similar to CS [34]. Additionally, sensory conflict seems to have an impact on both. But the sensory conflict in a car and VR are very different.

When travelling by car, one might perceive acceleration, but their visual surroundings, the vehicle's interior, remain still. This causes motion sickness. According to the SCT, you can lessen the conflict by gazing out the window, bringing the vestibular and visual information back into alignment. In VR, the conflict is going in the opposite direction. While the vestibular sense either detects no motion or is out of sync with the visuals, VR users perceive motion and accelerations through visual cues. This affects how CS is treated differently from traditional motion sickness.

#### 2) *Vection*

Vection, which refers to the perception of motion through visual stimuli, has frequently been linked to Visually Induced Motion Sickness (VIMS) or CS [35][36]. However, according to other research, vection can happen even when no sickness is present [35]. This shows there is more to the relationship between vection and CS than just a straightforward causal one. In their study, [36], who intended to further explore this connection, discovered that sickness is caused by a shift in vection [36]. From the standpoint of sensory conflict, it does make sense that CS is more often caused by apparent visual acceleration than by continuous visual motion. Conflict happens when one reason detects acceleration while the other does not since the vestibular system can only detect accelerations.

However, the findings of [37] are at odds with those of the study by [36] VIMS was not significantly impacted by the vection's strength or fluctuation. It is posited that [37] may have yet to be able to successfully create a high level of motion sickness, which might account for these conflicting results. Therefore, any potential difference in the ability to generate motion sickness between constant and variable vection may have yet to be able to achieve statistical significance. Humans acquire information about body motion through their vestibular system, which detects the rotational and translational accelerations of the head, in addition to visual data. Therefore, combined with the visual system, the vestibular system is a crucial tool for humans to notice when our body is moving and distinguish between object motion and self-motion [38][39]. When you start moving in VR with a joystick, something other than this multisensory integration may work better. There is a sensory conflict since you can feel vection. Still, the vestibular system doesn't send any signals of self-motion.

#### 3) *Postural Instability*

Postural instability, a notion that [41] first proposed, is another theory that is frequently brought up. They suggested that symptoms happen when you have not learned how to maintain yourself in that particular situation and are experiencing postural instability. When riding a roller coaster in VR while standing, you might be familiar with this sensation of instability. Various studies appear to contradict one another, with some offering evidence for the theory [42][43], while others either only discovered postural instability as a result of CS or found no causal relationship at all [44]. It still needs to be determined what the exact relationship with CS is. However, this idea offers a foundation for measuring CS objectively.

#### 4) *Rest-Frame Hypothesis*

The Rest-Frame Hypothesis is another theory that has influenced a typical CS mitigation technique [45]. According to this theory, CS results from the inability to identify or select a stable reference frame, also known as the rest-frame, from which to interpret relative movements, locations, and orientations. The nervous system chooses the rest-frame from among the various reference frames and gives it spatial-perceptual data [45]. According to the theory, the cognitive conflict that results from being unable to identify a single rest-frame compatible with a person's inertial and visual motion signals, rather than the sensory conflict, causes CS [40]. In other words, illness is more likely to be affected by how the user interprets what is moving and what is not based on the degree of competing cues.

### B. *Cybersickness Measurement Methods*

As covered in the section above, there are only a few well-established theories on CS. Similar to this, subjective and objective approaches to assessing CS exist, categorized into physiological state, postural sway, and questionnaires.

#### 1) *Questionnaires*

The Simulator Sickness Questionnaire (SSQ) is used in most articles. Even though this questionnaire was first developed for military simulators (like flight simulators), it is still the most well-known for CS in VR research. From none to severe, participants assess the severity of 16 symptoms on a 4-point scale. The results are divided into four scores: overall score, nausea, oculomotor, and disorientation. Several researchers have suggested alternatives because the SSQ's primary intent was not VR and was evaluated on highly skilled professionals [46][47]. Both the Cyber Sickness Questionnaire (CSQ) and the Virtual Reality Sickness Questionnaire (VRSQ) published by [46] and [48] can be seen as subgroups of the SSQ. Only nine symptoms remain when the nausea-related symptoms are excluded from the VRSQ.

The Fast Motion Sickness Measure (FMS) is a one-dimensional scale that ranges from zero to 20. This scale which indicates no motion sickness (zero) to severe motion sickness (20), was developed by [49]. It is feasible to gauge the time of the motion sickness since participants vocally rate each minute. The FMS and the SSQ score and its sub scores also show a substantial correlation in other research [49][50]. The Misery Scale (MISC) was developed by

Wertheim et al. as an alternative to the FMS. The scale extends from zero (no symptoms), to ten (vomiting). In addition to verbal responses, a physical dial may also be used to record answers on a one-dimensional illness scale, as [51] study showed.

It might be essential to know a participant's vulnerability to motion sickness in addition to measuring CS during or after a VR session. Participants' susceptibilities to CS can vary. Thus [52] updated Motion Sickness Susceptibility Questionnaire (MSSQ) was developed to gauge this. The participant's history of motion sickness is examined using the MSSQ. The Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ), which looks at prior encounters with symptoms rather than motion sickness in general, was created by [49] since this questionnaire was not designed for CS (or VIMS). [53] also suggested and examined a condensed version of the VIMSSQ in another research study due to its length.

#### 2) *Physiological State*

Although questionnaires are the most popular way to detect CS, they have certain drawbacks. First, surveys interfere with the user's experience, making it impossible to track their illness in real-time [54]. The fact that surveys are inherently subjective is another disadvantage. As a result, they only sometimes accurately gauge what they are attempting to perform. Researchers can assess the physiological status of the consumers to get past these issues. This is doable in real time and may offer a source of unbiased data.

The user's present status might be assessed by sensors, which would subsequently apply the appropriate CS mitigation techniques. A method that can evaluate CS in real-time using physiological data was developed by many researchers using machine learning [44][55]. Based on physiological data, such as heart rate, breath rate, heart rate variability, and galvanic skin reaction, [55] created an entirely closed-loop system. Based on the determined amount of sickness, it applied Field of View (FOV) reduction or Gaussian blurring, which might lower the level of nausea. The degree of CS was determined by periodically evaluating the user's physiological data. The system's capacity to lessen CS was not put to the test.

Despite being objective, physiological evidence has not been able to displace the SSQ as the gold standard for assessing CS. Physiological outcomes have often been employed in research to support their conclusions rather than as the primary measurement technique. Additionally, the SSQ or other questionnaires frequently validate physiological measures. Therefore, their validity is dependent on arbitrary information.

#### 3) *Posturial Sway*

Postural sway, which is a type of body movement, has yet to be included in several investigations as an impartial evaluation technique, even if the relationship between postural instability and CS still needs to be fully understood [56]. [57] showed that gait metrics may also be measured to determine CS. They recorded the necessary data using an inertial measurement unit on each foot. They then used a support vector machine which is a machine learning model to create a classifier for CS.

Using a balancing board to measure movements around the center of gravity is one method of documenting postural instability [42][58][60]. After analyzing their data, [58] identified the precise postural sway characteristics that might predict VIMS. According to the findings, those who reported feeling worse had postures that were more circular in form (as opposed to elliptical) and had a higher frequency of forward/backward oscillations. According to each participant's postural sway, [60] trained a deep, short-term memory model that may forecast their likelihood of experiencing CS.

However, there are also sensors in users' Head Mounted Displays (HMD) that may capture postural sway. Head dispersion, or the change in roll and pitch, was put to the test by [59] and shown to be significantly connected to changes on the x- and y-axis around the center of gravity. Participants had to hold their heads motionless or stare straight ahead to assess head dispersion. The relationship between the location information from the HMD and CS was also examined by [61]. They found strong correlations between a few location factors and the SSQ scores, even though the data was pretty noisy. These findings imply that it may be feasible to design a system that collects the HMD's location data, calculates the user's level of CS in real-time, and utilizes that information to modify the methods for reducing sickness.

## III. METHODOLOGY

### A. *Introduction*

This research is conducted using a SLR, defined as "*a means of identifying, evaluating and interpreting all available research to a particular research question, or topic area, or phenomenon of interest*" [6]. Simply put, an SLR is a review of primary studies. This study follows the SLR guidelines by [6], which are: identifying sources, study selection, data extraction, data synthesis and writing up the study as a report.

### B. *Search Terms used in selected databases*

"Virtual Reality" AND ("cybersickness" OR "motion sickness" OR "simulator sickness") AND ("factors" OR "fail" OR "break down" OR "flounder" OR "blunder" OR "flop" OR "deteriorate" OR "challenge" OR "issue" OR "problem" OR "obstacle*" OR "success" OR "accomplish" OR "achieve" OR "advance" OR "progress*" OR "realisation" OR "triumph" OR "victory" OR "fruition" OR "attainment" OR "model" OR "method" OR "framework").

#### 1) *Source Selection*

The following data sources were selected to perform the search:

- IEEE Xplore Digital Library
- Scopus
- ACM Digital Library
- Google Scholar

All of these databases are well-known research repositories in the field of information technology. In addition, Google Scholar was employed to help locate sources via backward and forward citation searches.

#### 2) *Selection Criteria*

The selection of research material for inclusion in this systematic review was based on this section's inclusion and exclusion criteria.

For a source to be included in the research, it had to meet the following criteria:

- Papers describing the factors that, in a VR setting, lead to cybersickness.
- Papers containing at least three keywords in the title, abstract, or keywords were chosen.

- Journal articles, conference papers, book chapters, dissertations and theses were considered.
- No limitations on publication date.

A source is excluded from the research for the following reasons:

- Papers that don't discuss the factors that contribute to cybersickness in a virtual reality setting.
- Non-English language academic papers.
- If the full text of the publication is not available.
- Duplicate papers meaning the same paper retrieved from different databases.

#### *3) Prisma Flowchart*

The search string above was performed on the selected databases, returning 1231 articles. The Google Scholar citation search found an additional ten records. After that, 219 duplicate papers were removed. Screening by the title and abstract was conducted, leaving 213 full-text articles. These full-text articles were further assessed for eligibility resulting in 28 remaining articles used for data extraction and synthesis (see Figure 1). The search was completed in August 2022.

#### *4) Quality Assessment*

The included papers were assessed using four quality assessment questions. The questions aimed to evaluate the quality aspects mentioned by [6]. These aspects are characterized as **objectivity** - if the research is free of bias; **reliability** - the accuracy and reliability of the research instruments used; **internal validity** - whether the research was well structured, so data was collected from suitable sources, and **external validity** - determines if the findings can be predicted for subsequent occasions.

Therefore, the following questions were devised to assess the quality of the selected literature:

Q1. Is Virtual Reality and Cybersickness factors the center of the discussion?

Q2. Does the research have a clear goal in mind?

Q3. Does the article clearly follow a research process and describe the data analysis techniques used?

Q4. Does the article report its findings based on evidence and argument?

These questions had three possible answers: Yes and No. Each response is given the following weighting: Yes = 1 and No = 0. The final score was noted and utilized as a scale from 0 to 4 to represent the overall quality of the chosen literature. The articles' outcomes and quality rating are displayed in the results section.

### *C. Data Extraction*

The data extraction was carried out on 28 papers included in the SLR. Thereafter, a qualitative thematic analysis was conducted to synthesize the extracted data. Some of the article's content was highlighted in the paper while it was being read. These ideas/concepts, usually referred to as codes, were carefully investigated to group them into common themes. All the pertinent information that helped in answering the research question was extracted, including the citation, the journal article or conference title, the source database, year published and study type, article sub-concepts, and the main concept. Google Sheets were used to extract data for the thematic analysis.

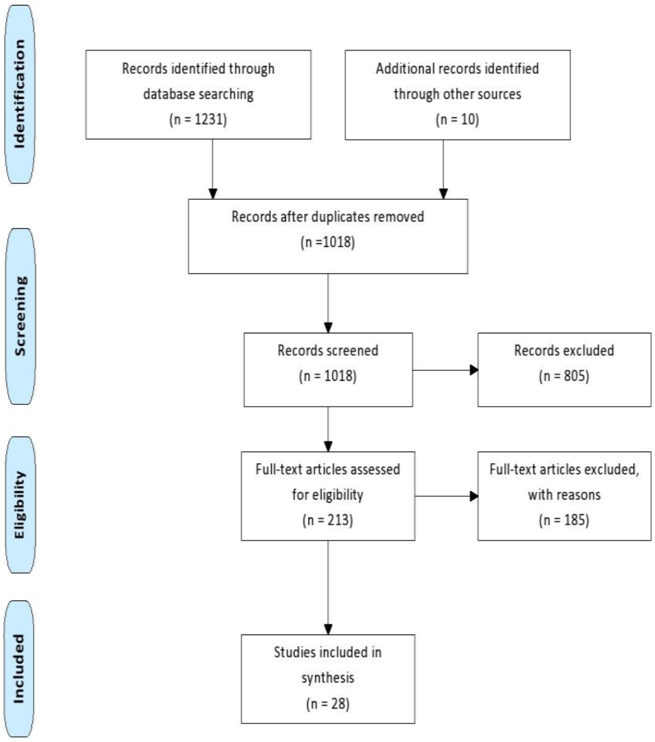


Figure 1. Prisma Flowchart.

## IV. RESULTS

### *A. Search Results*

The articles listed in the source selection section were looked at in four databases, which includes Google Scholar. Figure 2 displays the percentage distribution. Most of the articles came from IEEE Explore (41.8%). Scopus accounted for 40.3% and ACM digital library 12.9%. Ten articles (5%) derived from the Google Scholar citation searches.

Most papers included many factors, while some focused on one specific factor. Table I lists these 21 factors and their sources.

### *B. Quality Evaluation of Articles*

Four questions were used to assess the quality of the selected literature, as mentioned earlier. Most papers were of good quality, with an average score of 3.75 out of 4. No paper scored below 3.

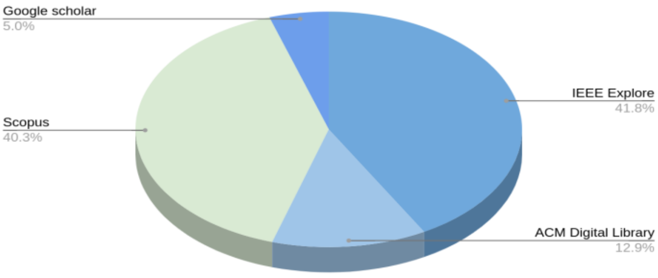


Figure 2. Database articles percentage distribution.

TABLE I. VIRTUAL REALITY CYBERSICKNESS FACTORS WITH SOURCES

| Factor | Sources |
|---|---|
| Habituation | [7][8][9][10] |
| Duration | [4][7][8][9][11][12][13] |
| Environmental conditions | [14] |
| Physical Health | [4][8][15][16][17] |
| Posture | [4][13][18] |
| Gender | [4][7][9][12][14][15][19][20][21] |
| Age | [4][7][12][15][21][22] |
| Field of View | [7][8][11][12][23] |
| Flicker | [4][12][21][24] |
| Screen size | [7][24] |
| Head mounted displays | [1][5][9][12][14][24][25][26][27] |
| Lag and Frame Rate | [11][28] |
| Method of movement | [24][29] |
| Calibration | [4] |
| Position Tracking error | [21] |
| Head motion | [13] |
| Playing position | [7] |
| Locomotion | [7][11][12][30] |
| Immersion | [7][12][31] |
| Sensory support | [31] |
| Graphic Realism | [12] |

## C. Synthesis of Identified Factors

A thematic analysis was conducted to identify the core themes and subthemes within the selected literature. The factors were categorized under subthemes and grouped under a theme. Initially, 42 factors were identified as contributing to CS in a VR environment. Upon examination of the definitions of each of these factors and the references made to them by the authors of the selected literature, 21 factors were merged into others resulting in 21 final factors. The remaining 21 factors were further analysed to identify any additional relationships to help categorize them. Categorizing the factors helps to understand the more significant themes and gives deeper insight. The synthesis using a thematic analysis went through 5 iterations resulting in three themes, eight subthemes, and 21 factors. These three common themes were identified as User, Hardware, and Software. Table II lists the synthesized themes, subthemes and the contributing CS factors. A conceptual model depicting these concepts are shown in Figure 3.

TABLE II. SYNTHESIZED THEMES, SUBTHEMES AND FACTORS

| Themes | Subthemes | Factors |
|---|---|---|
| User | Experience | Habituation<br>Duration<br>Environmental Conditions |
|  | Physical attributes | Physical Health<br>Posture |
|  | Demographics | Gender<br>Age |
| Hardware | Device | Field of View<br>Screen Size<br>Flicker<br>Head Mounted Displays<br>Lag and Frame Rate |
|  | Tracking | Method of Movement<br>Calibration<br>Position Tracking Error<br>Head Motion |
| Software | Stabilizing information | Playing Position |
|  | Environment | Locomotion |
|  | Design | Immersion<br>Sensory Support<br>Graphic Realism |

# V. DISCUSSION

This section of the research aims to answer the three research questions. The core SLR themes identified are 1) User, 2) Hardware, and 3) Software. Each of these themes has sub-themes that translate into factors. The factors under each theme and subtheme are discussed next followed by the addressing the research questions.

## A. Factors Contributing to CS

*1) User:* There are differences in CS susceptibility at the user level. These factors include Age, Gender, Habituation, Duration, Environmental Conditions, Physical Health and Posture. Each of these factors are discussed below. These factors are grouped in the subthemes of Demographics, Experience and Physical Attributes.

a) *Demographics:* The Demographics subtheme consists of factors Age and Gender.

Age. According to the literature, younger persons are more resistant to simulation sickness [12]. After the age of 40, people's vestibular perception threshold, or the lowest signal recognized, decreases, rendering them more susceptible to simulation sickness [15]. [22], discovered changes in the postural balance between young and middle-aged test participants. Furthermore, postural balance deteriorates when people become older, which can contribute to illness.

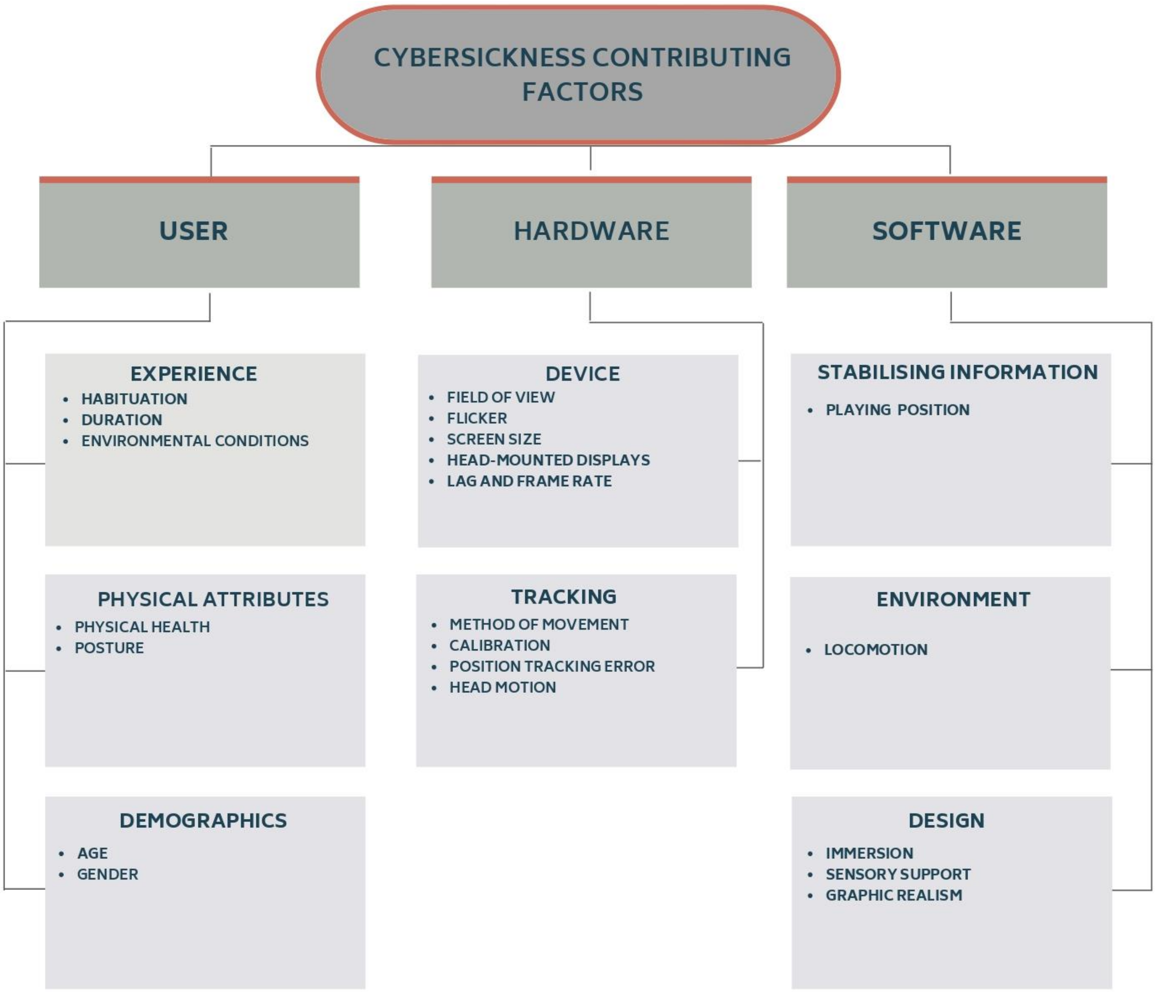


Figure 3. Virtual Reality Cybersickness Conceptual Model.

Gender. Females have consistently been found to be more susceptible than males to CS. With the usage of HMDs, CS may differ depending on gender. [20] investigated the influence of gender and technology and their possible contributions to simulation sickness. Using data from 223 people (108 men and 115 women), they investigated the degrees of simulation sickness concerning gender, sensory conflict, and advancements in VR technology. They concluded that women had a greater level of simulation sickness than males. [14] conducted many trials. They discovered that females were equally susceptible to motion sickness caused by an improper fit of the VR headgear to the inter-pupillary distance (the distance between the centre of one's eyes). They also propose that VR headsets be redesigned with adjustable interpupillary distance to decrease CS in women.

b) *Experience:* The Experience subtheme consists of factors Habituation, Environmental Conditions and Duration.

Habituation. According to [9], an increase in exposure time was directly related to the degree of unpleasant symptoms. Compared to non-susceptible individuals, those prone to motion sickness might suffer nearly double the severity. Users who feel nausea when riding carnival rides might expect to endure unpleasant sensations. Exposing a person to virtual surroundings briefly, halting the encounter before or during illness, and retrying in a day or two will assist the user in acclimatizing to the virtual world. Exposure to virtual settings regularly may reduce or eliminate simulation sickness.

Environmental conditions. CS symptoms worsen in environments with high temperatures and inadequate ventilation. Good airflow and ventilation can help reduce nausea and aid recovery after dizziness [14].

Duration. Several studies have found that more than 10 minutes of VR exposure can cause nausea, and the longer the exposure period, the more severe the VR sickness [7][8][11][12]. According to these studies, the application should allow users to pause the experience for a rest and then resume it later. In contrast, an application might advise users to take breaks regularly to avoid unpleasant sensations [11].

c) *Physical Attributes:* The Physical Attributes subtheme consists of factors Physical Health and Posture.

Physical Health. The user's senses must be at their peak to attain a heightened presence level. For the optimum VR experience, users should be physically fit and have a strong sense of balance. If a user has a hangover, cold, headache, is tired, or is sleep deprived, it is best to avoid a virtual environment since their symptoms may aggravate [11].

Posture. Postural instability is a well-documented consequence of exposure to a Virtual Environment (VE). Postural stability is frequently assessed before and after VE exposure to detect changes in stability caused by the exposure. Less posturally stable individuals are more likely to get CS or suffer from more severe illness when compared to more posturally stable individuals [4][13][18].

### 2) *Hardware*

Some factors associated with hardware used in a VE can induce CS. These include HMDs, Flicker, Field of View (FOV), Lag and Frame Rate, Screen Size, Method of Movement, Calibration, Position Tracking Error, and Head Motion. These factors are grouped in the subthemes of Device and Tracking.

a) *Device:* The Device subtheme consists of factors HMDs, Flicker, FOV, Lag and Frame Rate, and Screen Size.

Head-Mounted Displays (HMDs). When using HMDs, settings, such as contrast, light, exposure length, and operating distance all contribute to straining the visual system. When utilizing a stereoscopic HMD, such as EyePhone LX, in an immersive virtual world for 10 minutes, around 60% of respondents exhibited symptoms, such as eye strain, nausea, and headache, while 20% reported a loss in binocular visual perception [27]. Similar symptoms were reported by 61% of participants following twenty minutes of exposure to immersive virtual material using a DVisor HMD [26].

Technical developments in VR display technology, such as Oculus VR DK1 and Oculus VR DK2, did not significantly reduce CS [20]. Sensory conflict, however, plays a vital role in developing nausea and other symptoms. Body movement, confusion caused by head movement, and poor optical design led to strain-induced ocular pain. [1] recently observed that using HMDs caused more motion sickness than stereoscopic desktop displays. Some users stated that they felt more immersed in an HMD. However, they could only sustain the experience for a short period.

Flicker. Flicker has been extensively researched. The literature [4][12][21][24] suggests that flicker should be avoided at all costs. In a VR scenario, flicker is the brightness fluctuation on video screens that can cause nausea. This oscillation is visually disturbing and affects the user's eye health. When using larger displays, the user is likely to see flicker around the screen's edges. Avoiding flicker is crucial for HMDs with brighter panels and a high refresh rate [12]. Several components of the visual presentation influence flicker perception. The most relevant to visual displays or VR systems are the refresh rate, brightness level, and field of vision [4]. To reduce flicker, the refresh rate must increase as the brightness level increases [21].

Field of view (FOV). The display's horizontal and vertical angular dimensions are known as the FOV [23]. CS is more common in VE situations with a wide FOV than in those with a narrow FOV [7]. This is likely due to enhanced vection caused by higher peripheral retina stimulation from a broad FOV display [8]. A wide FOV also enhances the probability of detecting flicker [11]. This is because the peripheral visual system is more sensitive to flicker. To eliminate flicker, a broader FOV requires a quicker refresh rate [11].

Lag and Frame Rate. Latency is the time elapsed between the user's input and the visible response in a VE display. Frame rate measures how rapidly frames flow through the rendering process. A dip in frame rate might occur in a VR application with sophisticated visuals. Suppose the delay between user input and virtual content production is significant. In that case, there is a considerable risk of developing simulation sickness [11]. A suggested delay is 20 milliseconds; anything greater than 46 milliseconds might cause motion nausea. Companies, such as Oculus, Sony, and Steam stress the significance of virtual content with low latency, responsiveness, and fast frame rates for greater virtual content quality [28].

Screen size. Vection is highest in peripherally moving visual flow fields [7]. As a result, huge displays pose an increased risk of motion sickness. With full flow fields, virtually everyone will feel intense vection. As a general rule, the smaller the visual picture (or display), the lower the likelihood of CS [24]. Laboratory investigations have shown that the danger of vection is limited, with pictures reaching a viewing angle of fewer than 300 degrees [7]. A typical 17-inch computer screen, seen from a distance of 50 cm, contains 340 pixels and will not readily cause vection [7].

b) *Tracking:* The Tracking subtheme consists of the factor’s Method of Movement, Calibration, Position Tracking Error and Head Motion. These are discussed below.

Method of Movement. The VR user does not always have control over the character's motions. This lack of mobility can lead to significant problems. To satisfy sensory expectations, movement in a virtual world should be realistic. Inappropriate motions, such as quick tilting, rolling, and waveform motions, should be avoided. Gun sway, head bob, and moving up and down stairs are incorrect movements. According to [11], incorporating motions centered on leaps rather than continuous walks may help to reduce nausea. Uncontrolled user movement outputs should be restricted, such as flipping, falling, or zoom transitions [29].

Calibration. Because of variances in human physical traits, poor calibration exacerbates CS symptoms. Interpupillary distance, for example, the distance between the pupils' centers in both eyes, differs among persons [4]. Because stereoscopic displays require each eye to get a slightly offset image of the virtual world, this offset must be as near to the user's individual interpupillary distance as feasible. Calibration failure might result in greater spatial and temporal distortions, setting the scene for CS due to distorted graphics [4]. As a result, each individual requires suitable calibration. [4] believe that the right size, appropriate focus, and perfect alignment will aid in treating CS.

Position Tracking Error. The VR system's position-tracking error informs the computer about the location of the user's head and, presumably, limbs in the VE [21]. The system uses this data to create a graphical depiction of the user within the VE. If this information needs to be corrected, tracked items may appear in locations where they are not. If the tracked items are part of the user's body, the mismatch between where the graphical representation of the objects appears in the visual display and where the user believes they should appear may bother the user [21]. As a result, the illusion of the simulation may be broken, resulting in sickness-related symptoms, such as dizziness and loss of focus. Finally, location tracking mistakes might generate jitter or oscillations of portrayed body parts, which can be disturbing for users [21].

Head motion. According to [13], adopting a supine posture results in a considerable reduction in CS. They ascribed this to limited head mobility. Head movements are known to be related to CS via Coriolis and pseudo-Coriolis stimulation pathways [13]. When the head is tilted away from the axis of rotation during actual body rotation, Coriolis stimulation occurs [13]. When the head is inclined, apparent self-rotation is caused by visual cues, resulting in pseudo-Coriolis stimulation [13].

#### 3) *Software*

The characteristics of the software in a VE may impact the probability of CS. The theme is divided into three subthemes: Stabilizing Information, Environment, and Design. Playing Position, Locomotion, Immersion, Sensory Support, and Graphic Realism are contributing factors.

a) *Stabilizing Information:* The stabilizing information subtheme consists of the Playing Position factor.

Playing Position. [13] revealed that a significant reduction in CS occurs when individuals assume a supine position, probably due to limited head mobility. Subjects are expected to be seated or standing in most circumstances within a VE [7]. Because of the lower demands on postural control, sitting patients would experience less illness, according to [7].

b) *Environment:* The Environment subtheme consists of the factor Locomotion.

Locomotion. A vital factor in VE discomfort is accelerated movement or speed. Sensory conflicts that can cause discrepancies occur due to sudden increased or decreased acceleration. Therefore, increasing or decreasing acceleration slowly would result in a pleasant user experience [11]. Rapidly zoomed movements should also be avoided, such as when the visual cones move faster than expected when a user’s view is zoomed in [30].

c) *Design:* The Design subtheme consists of factors Immersion, Sensory Support and Graphic Realism.

Immersion. [5] studied the impact of virtual content type on simulation sickness. They noticed that the type of video content, immersive vs. non-immersive, is a critical factor for VE usability. Video content type influenced the contributor’s sensitivity to simulation sickness and physiology. Their conclusion was based on the results of a Simulation Sickness Questionnaire (SSQ) and other physiological measures. The lowest SSQ score was recorded for non-immersive virtual content displayed on a television screen, while the highest scores were reported on an HMD with immersive content [5].

Sensory Support. A user might experience higher VR immersion and expect relevant vestibular information after exposure to strong illusions. The system can cause motion sickness if the VR system cannot provide suitable sensory input [31]. Therefore, designing a logical environment in which the players can focus and bind is essential. The user interface elements should be fixed rather than floating, creating an environment with a clear, steady horizon and reference points that users can focus on to minimize sickness. A world with imbalanced or changing backgrounds should be avoided. Designing a virtual world that supports human sensory systems is ideal [31].

Graphic Realism. [12] investigated the results of rendering realistic scenes. Participants who experienced realistic graphic content were prone to a higher level of simulation sickness. The authors also suspect that a sensory discrepancy between the vestibular and visual systems may cause a higher level of discomfort.

### B. *Answering the research questions*

#### 1) *What are the causes of cybersickness in the Virtual Reality environment?*

A literature review was done in an attempt to understand the reasons why individuals become cyber sick in a VR environment. The Sensory Conflict Hypothesis was the CS theory discovered to be the most often discussed in the literature. According to the hypothesis, illness results from an imbalance between two sensory systems, the vestibular and visual systems. Other research identifies postural instability or the absence of a rest-frame, a fixed reference frame, contributing to CS [41]. However, experiencing motion sickness in VR can potentially lead to postural instability.

#### 2) *How can the severity of cybersickness experienced, or susceptibility to it be assessed before, during, or following a session?*

To provide an answer to this question, a literature review was conducted. According to the literature there are several objective and subjective techniques to gauge one's vulnerability to or degree of CS. Although the CSQ and VRSQ have shown superior validity for VR, according to the study of [47], the SSQ is still the most often used assessment technique. Examples of one-dimensional scales that let researchers quantify CS while participants are in VR are the FMS and MISC [49]. The MSSQ assesses prior experiences with motion sickness generally, whereas the VIMSSQ assesses susceptibility to CS [49].

In addition to surveys, the physiological condition also reveals how much CS individuals feel. The advantage of physiological data collection is that it can be done throughout the VR experience and is a reliable source of factual information. Measuring the characteristics of gait or postural sway is another technique to obtain objective data. CS was shown to be connected with specific VR headset positional and rotational features by [67].

#### 3) *Which factors contribute to Cybersickness during the application of Virtual Reality technologies?*

A systematic review was conducted to answer this question. Systematic reviews deliver an orderly, clear means for gathering, synthesizing and evaluating the results of studies on a specific topic or question [32]. The purpose of a systematic review is to minimize the bias linked with solitary studies and non-systematic reviews [32]. A thematic analysis was used to identify the core themes and factors within the selected literature.

Twenty-eight publications were included in the systematic review based on four carefully chosen databases. Twenty-one factors were found to contribute to CS during the application of VR technologies. These factors are Age, Calibration, Duration, Environmental Conditions, Field of View, Flicker, Gender, Graphic Realism, Habituation, Head Motion, Head Mounted Displays, Immersion, Lag and Frame Rate, Locomotion, Method of Movement, Physical Health, Playing Position, Position Tracking Error, Posture, Screen Size, and Sensory Support. As a result, a conceptual model of the factors that lead to CS has been developed.

## VI. CONCLUSION

The primary goal of this study was to identify and describe the factors that contribute to CyberSickness (CS) in a Virtual Reality (VR) environment. This was achieved through a SLR and thematic analysis. A model of the factors that lead to CS has been developed to aid in the study of CS in VR.

After conducting this study, it became clear that CS is a multifaceted issue. At present, there is no silver bullet solution. Fortunately, many solutions have been thought of already. Some are more effective than others. We can get closer to a VR experience potentially free of CS by testing and further investigating CS and its underlying mechanisms. One-by-one CS-inducing factors could be reduced if not eliminated.

Limitations of this study are, firstly, only English-language publications were considered. Therefore, data that might be pertinent to the research question but was written in a different language is excluded from this study. Second, just four data sources were utilized to do the SLR; as a result, it's possible that relevant material from other databases was missed. Third, there is a chance that the SLR's search string is not rigorous enough, which might have left out essential themes and factors.

Future researchers and practitioners can evaluate the factors that lead to CS in a VR environment using the model developed. Similar research should also be conducted to support or refute this study's factors and themes.

## REFERENCES

[1] C. Yildirim, “Don’t make me sick: investigating the incidence of cybersickness in commercial virtual reality headsets”. *Virtual Reality, 24, no. 2*, pp. 231-239, 2020.

[2] K. Berntsen, R. C. Palacios, and E. Herranz, “Virtual reality and its uses: a systematic literature review”. In *Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality*, pp. 435-439, 2016.

[3] L. Rebenitsch and C. Owen, “Review on cybersickness in applications and visual displays”. *Virtual Reality*, *20, no. 2*, pp. 101-125, 2016.

[4] S. Davis, K. Nesbitt, and E. Nalivaiko, “A systematic review of cybersickness”. In *Proceedings of the 2014 conference on interactive entertainment*, pp. 1-9, 2014.

[5] J. Guna et al., “Virtual reality sickness and challenges behind different technology and content settings”. *Mobile Networks and Applications*, *25, no. 4*, pp. 1436-1445, 2020.

[6] B. Kitchenham, Procedures for performing systematic reviews. *Keele, UK, Keele University*, *33*, pp. 1-26, 2004.

[7] L. Rebenitsch, “Managing cybersickness in virtual reality”. *XRDS: Crossroads, The ACM Magazine for Students*, *22, no. 1*, pp. 46-51, 2015.

[8] L. Rebenitsch and C. Owen, “Individual variation in susceptibility to cybersickness”. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*, pp. 309-317, 2014.

[9] K. M. Stanney, K.S. Hale, I. Nahmens, and R. S. Kennedy, “What to expect from immersive virtual environment exposure: Influences of gender, body mass index, and past experience”. *Human factors*, *45, no. 3*, pp. 504-520, 2003.

[10] L. Rebenitsch and B. Quinby, “Cybersickness and postural sway using hmd orientation”. In *International conference on human-computer interaction*, Springer, Cham, pp. 500-509, 2019.

[11] T. M. Porcino, E. Clua, D. Trevisan, C. N. Vasconcelos, and L. Valente, “Minimizing cyber sickness in head mounted display systems: design guidelines and applications”. In *2017 IEEE 5th international conference on serious games and applications for health (SeGAH)*, IEEE, pp. 1-6, 2017.

[12] E. Chang, H. T. Kim, and B. Yoo, “Virtual reality sickness: a review of causes and measurements”. *International Journal of Human–Computer Interaction*, *36, no. 17*, pp. 1658-1682, 2020.

[13] G. Wang and A. Suh, “User adaptation to cybersickness in virtual reality: a qualitative study”. In *27th European Conference on Information Systems (ECIS 2019): Information Systems for a Sharing Society*. Association for Information Systems (AIS), 2019.

[14] K. Stanney, C. Fidopiastis, and L. Foster, “Virtual reality is sexist: but it does not have to be”. *Frontiers in Robotics and AI*, *7*, 4, 2020.

[15] M. Mousavi, Y. H. Jen, and S. N. B. Musa, “A review on cybersickness and usability in virtual environments”. In *Advanced engineering forum*, vol. 10. Trans Tech Publications Ltd, pp. 34-39, 2013.

[16] S. Bruck and P. A. Watters, “The factor structure of cybersickness”. *Displays, 32*, no. 4, pp. 153-158, 2011.

[17] A. K. Ng, C. H. Leung, L. K. Chan, and H.Y. Lau, “Human Factors Related to Cybersickness Tolerance in Virtual Environment”. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, pp. 528-532, 2022.

[18] S. Ang and J. Quarles, “You’re in for a Bumpy Ride! Uneven Terrain Increases Cybersickness While Navigating with Head Mounted Displays”. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, pp. 428-435, 2022.

[19] K. Stanney et al., “Identifying causes of and solutions for cybersickness in immersive technology: reformulation of a research and development agenda”. *International Journal of Human–Computer Interaction*, *36, no. 19*, pp. 1783-1803, 2020.

[20] D. M. Shafer, C. P. Carbonara, and M. F. Korpi, “Modern virtual reality technology: cybersickness, sense of presence, and gender”. *Media Psychology Review*, *11, no. 2*, 1, 2017.

[21] J. J. LaViola Jr, “A discussion of cybersickness in virtual environments”. *ACM Sigchi Bulletin*, *32, no. 1*, pp. 47-56, 2000.

[22] P. Era, P. Sainio, S. Koskinen, P. Haavisto, M. Vaara, and A. Aromaa. “Postural balance in a random sample of 7,979 subjects aged 30 years and over”. *Gerontology*, *52, no. 4*, pp. 204-213, 2006.

[23] J. Teixeira and S. Palmisano, “Effects of dynamic field-of-view restriction on cybersickness and presence in HMD-based virtual reality”. *Virtual Reality*, *25, no. 2*, pp. 433-445, 2021.

[24] W. Bles, and A. H. Wertheim, “*Appropriate use of virtual environments to minimise motion sickness”*. Human Factors Research Inst Tno Soesterberg (Netherlands), 2001.

[25] D. Saredakis et al., “Factors associated with virtual reality sickness in head-mounted displays: a systematic review and meta-analysis”. *Frontiers in human neuroscience*, *14*, 96, 2020.

[26] P. Caserman, A. Garcia-Agundez, A. Gámez Zerban, and S. Göbel, “Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook”. *Virtual Reality*, *25, no. 4*, pp. 1153-1170, 2021.

[27] M. Mon-Williams, J. P. Warm, and S. Rushton, “Binocular vision in a virtual world: visual deficits following the wearing of a head-mounted display”. *Ophthalmic and Physiological Optics*, *13, no. 4*, pp. 387-391, 1993.

[28] K. Raaen and I. Kjellmo, “Measuring latency in virtual reality systems”. In *International Conference on Entertainment Computing*. Springer, Cham, pp. 457-462, 2015.

[29] S. Sharples, S. Cobb, A. Moody, and J. R. Wilson, “Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems”. *Displays*, *29, no. 2*, pp. 58-69, 2008.

[30] Y. Farmani and R. J. Teather, “Evaluating discrete viewpoint control to reduce cybersickness in virtual reality”. *Virtual Reality*, *24, no. 4*, pp. 645-664, 2020.

[31] Y. Y. Kim et al., “The application of biosignal feedback for reducing cybersickness from exposure to a virtual environment”. *Presence: Teleoperators and Virtual Environments*, *17, no. 1*, pp. 1-16, 2008.

[32] J. Jesson, L. Matheson, and F. M. Lacey, “Doing your systematic review-Traditional and systematic techniques”. *International Journal of STEM Education*, 2020.

[33] M. C. Howard and E. C. Van Zandt, “A meta-analysis of the virtual reality problem: Unequal effects of virtual reality sickness across individual differences”. *Virtual Reality*, *25, no. 4*, pp. 1221-1246, 2021.

[34] A. M. Gavgani, K. V. Nesbitt, K. L. Blackmore, and E. Nalivaiko, “Profiling subjective symptoms and autonomic changes associated with cybersickness”. *Autonomic Neuroscience*, 203, pp. 41-50, 2017.

[35] R. H. So, W. T. Lo, and A. T. Ho, “Effects of navigation speed on motion sickness caused by an immersive virtual environment”. *Human factors*, *43* no. 3, pp. 452-461, 2001.

[36] F. Bonato, A. Bubka, S. Palmisano, D. Phillip, and G. Moreno, “Vection change exacerbates simulator sickness in virtual environments”. Presence: *Teleoperators and Virtual Environments*, *17*, no. 3, pp. 283-292, 2008.

[37] O. X. Kuiper, J. E. Bos, and C. Diels, “Vection does not necessitate visually induced motion sickness”. *Displays*, *58*, pp. 82-87, 2019.

[38] M. W. Greenlee et al., “Multisensory integration in self motion perception”. *Multisensory Research*, *29*, no. 6-7, pp. 525-556, 2016.

[39] A. M. Green and D. E. Angelaki, “Multisensory integration: resolving sensory ambiguities to build novel representations”. *Current opinion in neurobiology*, *20, no. 3*, pp. 353-360, 2010.

[40] A. Delorme and C. Martin, “Roles of retinal periphery and depth periphery in linear vection and visual control of standing in humans”. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *40, no.2*, 176, 1986.

[41] G. E. Riccio and T. A. Stoffregen, “An ecological theory of motion sickness and postural instability”. *Ecological psychology*, *3, no. 3*, pp. 195-240, 1991.

[42] D. Risi and S. Palmisano, “Effects of postural stability, active control, exposure duration and repeated exposures on HMD induced cybersickness”. *Displays*, 60, pp. 9-17, 2019.

[43] S. Litleskare, “The relationship between postural stability and cybersickness: it's complicated–an experimental trial assessing practical implications of cybersickness etiology”. *Physiology & behavior*, 236, 113422, 2021.

[44] M. S. Dennison and M. D’Zmura, “Cybersickness without the wobble: Experimental results speak against postural instability theory”. *Applied ergonomics*, 58, pp. 215-223, 2017.

[45] E. Chang et al., “Effects of rest frames on cybersickness and oscillatory brain activity”. In 2013 *International winter workshop on brain-computer interface (BCI)*. IEEE, pp. 62-64, 2013.

[46] W. B. Stone III, Psychometric evaluation of the Simulator Sickness Questionnaire as a measure of cybersickness (*Doctoral dissertation, Iowa State University*), 2017.

[47] V. Sevinc, and M. I. Berkman, “Psychometric evaluation of Simulator Sickness Questionnaire and its variants as a measure of cybersickness in consumer virtual environments”. *Applied ergonomics*, 82, 102958, 2020.

[48] H. K. Kim, J. Park, Y. Choi, and M. Choe, “Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment”. *Applied ergonomics*, 69, pp. 66-73, 2018.

[49] B. Keshavarz, and H. Hecht, “Validating an efficient method to quantify motion sickness”. *Human factors*, 53, no. 4, pp. 415-426, 2011.

[50] R. Reinhard et al., “The best way to assess visually induced motion sickness in a fixed-base driving simulator”. *Transportation research part F: traffic psychology and behaviour*, 48, pp. 74-88, 2017.

[51] N. McHugh, S. Jung, S. Hoermann, and R. W. Lindeman, “Investigating a physical dial as a measurement tool for cybersickness in virtual reality”. In Proceedings of the 25th ACM *Symposium on Virtual Reality Software and Technology*, pp. 1-5, 2019.

[52] J. F. Golding, “Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness”. *Brain research bulletin*, *47*, no. 5, pp. 507-516, 1998.

[53] J. F. Golding, A. Rafiq, and B. Keshavarz, “Predicting individual susceptibility to visually induced motion sickness by questionnaire”. *Frontiers in Virtual Reality*, 2, 576871, 2021.

[54] E. Nalivaiko, S. L. Davis, K. L. Blackmore, A. Vakulin, and K. V. Nesbitt, “Cybersickness provoked by head-mounted display affects cutaneous vascular tone, heart rate and reaction time”. *Physiology & behavior*, 151, pp. 583-590, 2015.

[55] R. Islam, S. Ang, and J. Quarles, Cybersense: “A closed-loop framework to detect cybersickness severity and adaptively apply reduction techniques”. *In 2021 IEEE Conference on virtual reality and 3d user interfaces abstracts and workshops (VRW)*. IEEE, pp. 148-155, 2021.

[56] E. Chang, H. T. Kim, and B. Yoo, “Virtual reality sickness: a review of causes and measurements”. *International Journal of Human–Computer Interaction*, *36*, no. 17, pp. 1658-1682, 2020.

[57] T. Feigl et al., “Sick moves! motion parameters as indicators of simulator sickness”. *IEEE transactions on visualization and computer graphics*, *25*, no. 11, pp. 3146-3157, 2019.

[58] J. R. Chardonnet, M. A. Mirzaei, and F. Mérienne, “Features of the postural sway signal as indicators to estimate and predict visually induced motion sickness in virtual reality”. *International Journal of Human–Computer Interaction*, *33*, no. 10, pp. 771-785, 2017.

[59] K. Lim, J. Lee, K. Won, N. Kala, and T. Lee, “A novel method for VR sickness reduction based on dynamic field of view processing”. *Virtual Reality*, 25, pp. 331-340, 2021.

[60] G. Wang and S. Ayoung, "User adaptation to cybersickness in virtual reality: a qualitative study". In Proceedings of the 27th European Conference on Information Systems (ECIS), Stockholm & Uppsala, Sweden, June 8-14, pp. 5-15, 2019. ISBN 978-1-7336325-0-8 Research Papers.

[61] L. Rebenitsch and B. Quinby, “Cybersickness and postural sway using HMD orientation”. *In Virtual, Augmented and Mixed Reality. Multimodal Interaction: 11th International Conference, VAMR 2019, Held as Part of the 21st HCI International Conference*, HCII 2019, Orlando, FL, USA, July 26–31, 2019, Proceedings, Part I 21, Springer International Publishing, pp. 500-509, 2019.

# Autonomic Pulse Communications for Adaptive Transmission Range in Decentralised Robot Swarms

Liam McGuigan, Roy Sterritt, Glenn Hawe
School of Computing, Faculty of Computing, Engineering and the Built Environment
Ulster University
Jordanstown, N. Ireland
email: mcguigan-l8@ulster.ac.uk, r.sterritt@ulster.ac.uk, gi.hawe@ulster.ac.uk

***Abstract*— Robot swarms, consisting of large numbers of individual robots collectively working towards a common goal, must be autonomous in order to carry out their task without regular human input. Further, there is a requirement that such swarms be autonomic, capable of self-management to enable operation in distant, complex or changing environments. Underpinning the ability of the swarm to cooperate and adapt is the communication between individual robots. Wireless communication relying on a fixed transmission range may be subject to connectivity loss, restrain robot motion, or be an inefficient use of energy. This research makes use of robot swarm simulation to develop Autonomic Pulse Communication as a means of adaptively selecting a transmission range, based on the existing concept of Pulse Monitoring to allow individuals within the swarm to estimate the local swarm density. The system is able to successfully share data originating in a single robot with the rest of the swarm within an allotted time period. It is also found to be extremely robust to communications loss, completing the task when the chance of a successful message receipt is as low as 5%.**

***Keywords- Swarm robotics; Self-adaptation; Autonomic Computing; Swarm communication; Simulation.***

## I. INTRODUCTION

Swarm robotics, the study of how individual behaviours within a group of robots may combine through local interactions to create a more complex set of behaviours [1], has potential applications in fields such as space exploration [2], precision agriculture [3], and disaster response [4], where many small, simple robots can cover a much larger area than a single monolithic craft.

The size of the swarm, its decentralised nature, and the conditions in which it may potentially operate mean that a swarm should be able to act on its own, adjusting its behaviour according to a changing situation without the need for any external guidance [5]. Autonomic Computing concepts [6][7] can assist in achieving swarm self-adaptation, making use of a Monitor, Analyse, Plan and Execute loop, with a shared Knowledge base, known as MAPE-K, as described in [6] to assess the situation, identify any changes necessary, and implement them.

As swarms are decentralised, their ability to adapt depends on their cooperation through sharing information on which to base decisions and come to an agreement on actions to be taken. When the swarms are reliant on local communication with neighbouring robots, the effective range of that communication matters. Too small, and robot behaviour may need to be constrained to maintain communication links with other members of the swarm. Too large, and it may be an inefficient use of battery power, lead to communication interference, or even be detrimental to overall performance.

In previous work, a decentralised swarm made use of an autonomic system to help adjust a range over which robots would broadcast for help in a foraging task [8]. This worked by using a fixed range pulse message between robots to help estimate the density, but it was found that the range of this pulse message needed to be set for differing swarm densities. If this is not initially known, performance would be degraded.

The objective of this work is to implement an adaptive system for setting the range over which a robot broadcasts information, according to the local density of the swarm, detected at run-time.

The rest of this paper is structured as follows. Section II discusses related work in swarm self-adaptation and autonomic systems used to develop the Autonomic Pulse Communication (APC) system presented. Section III discusses the design of the APC system and how it estimates local density. Section IV describes the data sharing task used, Section V describes the test scenarios used to evaluate the system, and Section VI presents the results of those tests. Section VII discusses the results, and Section VIII concludes the paper with a summary and directions for future research.

## II. RELATED WORK

In the context of a robot swarm, a distinction can be made between the adaptation of individual robots, and that of the swarm as a whole. This can be related to the idea of *self-expression* [9][10], in which the swarm at large can be reconfigured. Such swarm-level adaptation can then take advantage of wider knowledge to make changes to swarm composition [11], or cooperative strategies [12].

To achieve swarm-level adaptation, however, cooperation and communication becomes essential. Individuals must share data in order to collectively recognize the need to adapt, and then to decide on the new course of action. Consensus problems, typified in swarm research as the best-of-*n* problem [13], in turn require some means of communicating the currently held opinion of any one robot to neighbours.

Direct communication between neighbours requires a degree of connectivity between the robots in the swarm. All-time connectivity uses approaches such as control laws to balance both the task at hand and the need for connectivity [14][15]. Such approaches necessarily restrict the movement of individual robots, and may be detrimental to performance [16]. Relay approaches may help with this, by delegating the job of providing connectivity to only some portion of the swarm [17][18].

Relaxing the need for all-time connectivity, path planning approaches [16] or ferries [19] may allow for an intermittent approach, but add complexity to swarm behaviour and require some or all robots to halt their task periodically.

The absence of explicit attempts to maintain communications link may be described as opportunistic, with robots transferring data to others in range when their paths happen to cross. This is the least restrictive approach and does not require dedicated roles or periodic rendezvous, but at the expense of guaranteed connectivity.

A crucial factor, regardless of the approach taken, is the communication range. The further apart any two robots may be when maintaining a communication link between them, the freer the robots are to move, and the fewer the number of robots that may be critical to network connectivity. As higher ranges may require more power and result in network interference [20], and lower ranges may decrease connectivity, finding a suitable broadcast range becomes desirable.

The mechanism for achieving this, described in the next section, is based on the existing concept of Pulse Monitoring (abbreviated to PBM due to its extension of Heart Beat Monitoring, HBM) [21], in which a periodic heartbeat message has a pulse encoded within it, allowing a component in a system to indicate its current health status. The concept has been explored in applications such as personal computers [22], telecommunications [23], and cluster management [24]. In order to support a reflexive reaction by minimising the processing required by a recipient, health-related data may be included in the message [23].

Pulse monitoring may be applied to a robot swarm, such as in [25], where it may be a means for a ruler craft during the Prospecting Asteroid Mission to monitor the health of workers under their control. However, another perspective may be used. In a dynamic swarm, where there is a need for scalability, it may be undesirable for one robot to track another's health over a significant period of time, and it cannot be expected that any one robot would rely upon another *specific* robot to assist in a task. Instead, pulses received during a small interval may represent the health of the local neighbourhood, allowing a robot to determine if its own status is abnormal, or provide early-warning of danger by noting problems developing in neighbouring robots.

Pulse monitoring is typically concerned with reporting on the health of whatever aspect is being monitored, as a form of failure management. In this paper, the concept is adapted to allow an individual robot to measure the local density of the swarm through the receipt of pulse messages from neighbouring robots that contain information about the source robots' positions. In this way, the "I am healthy" signal is replaced with one saying "I am here". The design of the APC system is described in the next section.

## III. AUTONOMIC PULSE COMMUNICATIONS

The goal of the APC system described in this paper is to provide a mechanism for the adaptive adjustment of the transmission range used for inter-robot communication, in order to avoid the pitfalls that come with needing to set the range used at the start of the mission.

To achieve this, the concept of PBM described in the previous section is adapted to repurpose the regular signal sent by each robot. In the Decentralised Autonomic Manager described in [8], robots used periodic pulses to determine the local density of the swarm, but the pulse required a fixed transmission range used by each robot. If different transmission ranges were to be used, the density could not be easily calculated.

This problem is resolved by having each pulse also contain the position of the sending robot, allowing the distance from the pulse origin to the receiving robot to be calculated. Alternatively, situated communication [26] may be used to derive distance information from the received signal. Whichever approach is taken, the distance may be used to estimate the local density.

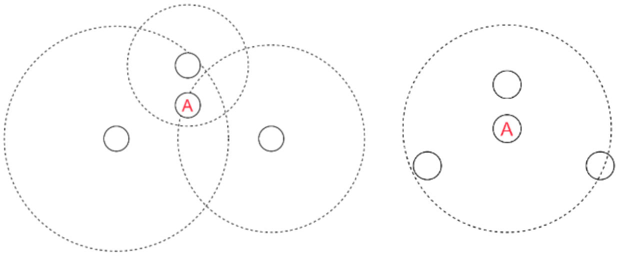
Fig. 1 (a) shows a case in which Robot A has a number of neighbours, all broadcasting pulse messages at different ranges, each of which is transmitted far enough to reach the robot. To simplify the example, all robots are shown to be sending their messages simultaneously, but the same process applies as long as all messages are received within the same short period of time. Each pulse contains the position of its sending robot.

By totalling the measured ranges of the received pulses, the APC system is able to calculate the average distance of pulse messages received. The local density, $\rho$, is then calculated as:

$$\rho = n / \pi\bar{d}^2, \tag{1}$$

where $n$ is the number of received pulses in the time period, and $\bar{d}$ is their mean distance.

Given a density, the APC system may then use a density-pulse range relationship provided in its knowledge base,



(a) (b)

Figure 1. A robot receives pulse messages from neighbours, and uses them to calculate a suitable range for its own pulse.

calculated based on the needs of the task. In Fig. 1 (b), Robot A sends out its own pulse, with the range determined by that relationship, enabling its pulse message to reach its neighbours.

The APC system is only able to calculate a suitable local density if it receives pulse messages during the period between sending its own pulses. If none are received, the robot is considered to be isolated from the rest of its swarm, and so it gradually increases its broadcast range on subsequent pulses. This increases the chance that the robot will later reconnect with the other robots, in turn influencing future selections of the transmission range.

In addition to the distance information required by the APC system, pulse messages may also share arbitrary data, sent on each broadcast, for the purpose of spreading information throughout the swarm. In this work, the data packet is small and does not grow with size, so a simple strategy of sharing data with neighbouring robots is used, in which no individual robot needs to care about which robots receive a broadcast. This approach scales with the swarm size, as the underlying behaviour of the robots does not need to change for larger swarms.

## IV. DATA SHARING TASK

This research employs a time-stepped simulation of a homogeneous swarm of agents tasked with sharing a piece of data throughout the swarm. The purpose of this task is to determine how well a swarm of robots may share a single piece of information, initially held by only one robot in the swarm, with the rest of the members. The swarm of robots, each using an APC system configured with a pulse period of 10 simulation ticks, and a fixed pulse range of 10 units, is placed in a circular map.

Each robot stores a Boolean flag, initially set to false. At the start of each run, a robot is selected at random from the swarm and their flag is set to true. Any robot whose flag is true will share this data via the APC system. Receipt of the flag will cause a robot to set its own flag to true, and commence its own sharing.

During the test, the robots may wander freely throughout the map. Each tick of the simulation, a robot picks a random direction in two dimensions. If the robot is able to move forward one unit distance without leaving the map, the robot moves to that location, otherwise it will not move in this simulation update.

The test is left to run for 250 simulation ticks, and at the end, the success of the swarm in sharing the data is scored by the percentage of robots with their flag set to true. The test duration used will impact the density-range calculation, as the ideal range data used will be that which enables the swarm to reliably share the data with all members within 250 ticks.

All tests were run with the APC system set to stagger pulse times, rather than having all robots pulse simultaneously. This removes any requirement of the APC system to synchronise robot behaviour, while also avoiding flooding the available bandwidth with messages sent simultaneously.

## V. TEST SCENARIOS

The following subsections describe the particular test scenarios run. Each test was run 50 times, and the results averaged across all runs.

### A. *Density-Pulse Range Relationship*

To determine the relationship between the swarm density and the ideal pulse range to use, a set of simulations was run, for swarm sizes of 50, 100, 200, 500 and 1,000 robots, and maps with radii of 25, 50, 75 and 100 units.

The ideal pulse range for a given combination was determined by taking the lowest pulse range for which over 99.5% of the swarm, on average, received the data.

### B. *Pulse Period*

This test explores how the APC pulse period affects the ability of the swarm to share the data. A map with a radius of 100 units was used, with the pulse range fixed at 10 units. The test was repeated with the five swarm sizes from the previous test, and pulse periods of 2, 5, 10, 15, 20 and 25 ticks. Each combination of swarm size and pulse period was tested, and the scores from each scenario are compared to evaluate the effects.

### C. *Adaptive Pulse Range*

The equation relating density and pulse range derived from the previous test is now used in the APC system to adaptively adjust the pulse range, based on the local swarm density. This test looks at the ability of this adaptive APC system to set an appropriate pulse range, and therefore share the data throughout the swarm.

The maps and robot counts are the same as those listed from the Density – Pulse Range tests. Each APC system starts with a pulse range of one unit, and uses a period of 10 ticks. The score for each combination of map and swarm size is measured, and compared against the best performing fixed range communication established in the previous test.

### D. *Communications Loss*

To explore the impact of communications no longer being guaranteed to arrive, a swarm of 200 robots is tested in a map with a radius of 100 units. The simulation is configured with a probability of any robot receiving a broadcast range, and the test is run with probabilities of 20%, 15%, 10%, 5%, 4%, 3%, 2% and 1%, together with a test of the fixed range communications with a probability of communication success set to 5%. Every 10 ticks, the number of robots that have the flag set to true are recorded, and the results compared.

## VI. RESULTS

The following subsections discuss the results of the tests described above.

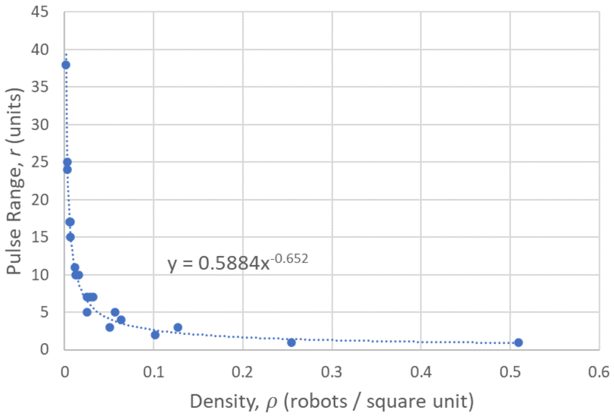


Figure 2. Plot of ideal pulse range against swarm density.

## A. Density-Pulse Range Relationship

Table I shows the best performing ranges and their respective scores for each combination of map radius and swarm size, while Fig. 2 shows the relationship between swarm density and best performing pulse range.

Fitting a trend line to the plot leads to an equation for determining the pulse range to use, given the density of the swarm:

$$r = 0.5884 \times \rho^{-0.652}, \qquad (2)$$

where $r$ is the pulse range, and $\rho$ is the swarm density.

## B. Pulse Period

Fig. 3 shows the performance for each size of swarm, as the pulse period is increased. Increasing the period results in a drop in the score achieved, which is less prominent in the largest swarms, and is most clearly seen with a swarm of 200 robots.

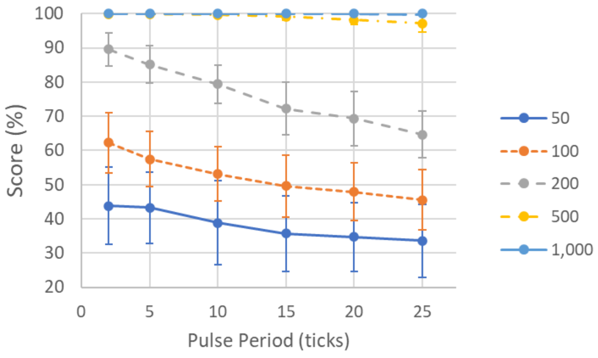


Figure 3. Score achieved by the swarm for each pulse period tested.

## C. Adaptive Pulse Range

Table II shows the performance of the swarm, and average pulse range used, for each combination of map radius and swarm size. All scenarios achieved greater than the 99.5% score used as a benchmark in the fixed range tests, and all but three of the scenarios received a perfect score. The average pulse range used by the swarm can be compared against the ideal fixed ranges shown in Table I, and shows that higher density swarms make use of shorter range pulses on average.

## D. Communications Loss

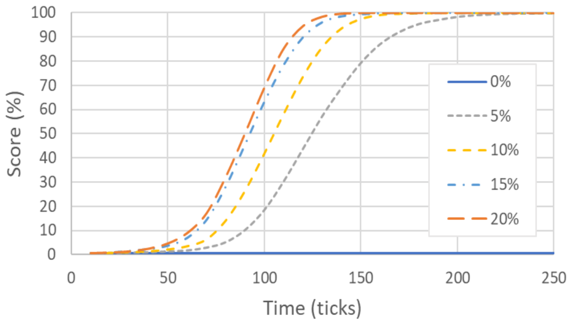
Fig. 4 shows the performance of the swarm of 200 robots on a map with a 100-unit radius, in scenarios where the probability of a communications broadcast being received by a robot was 20% or lower. In addition, the chart shows the performance of the APC system running with a fixed pulse range, where communications have a 5% probability of succeeding.

TABLE I. IDEAL PULSE RANGES FOR EACH MAP AND SWARM SIZE

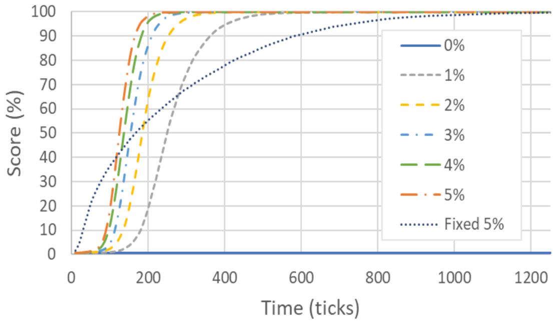
| **Swarm Size** | **Map Radius** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **25** | | **50** | | **75** | | **100** | |
| | Range | Score | Range | Score | Range | Score | Range | Score |
| 50 | 5 | 99.84% | 15 | 99.72% | 25 | 99.67% | 38 | 99.88% |
| 100 | 3 | 99.82% | 10 | 99.62% | 17 | 99.54% | 24 | 99.60% |
| 200 | 2 | 99.97% | 7 | 99.94% | 11 | 99.57% | 17 | 99.53% |
| 500 | 1 | 99.96% | 4 | 99.94% | 7 | 99.90% | 10 | 99.74% |
| 1,000 | 1 | 100% | 3 | 100% | 5 | 99.95% | 7 | 99.87% |

TABLE II. PULSE RANGES AND SCORES WHEN USING APC

| **Swarm Size** | **Map Radius** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **25** | | **50** | | **75** | | **100** | |
| | Range | Score | Range | Score | Range | Score | Range | Score |
| 50 | 7.28 ± 0.32 | 100% | 16.27 ± 0.33 | 100% | 23.34 ± 0.47 | 99.96% | 29.42 ± 0.51 | 99.64% |
| 100 | 4.61 ± 0.14 | 100% | 10.68 ± 0.21 | 100% | 16.50 ± 0.18 | 100% | 21.63 ± 0.26 | 99.98% |
| 200 | 3.04 ± 0.07 | 100% | 7.14 ± 0.13 | 100% | 11.06 ± 0.17 | 100% | 14.87 ± 0.19 | 100% |
| 500 | 1.89 ± 0.02 | 100% | 4.02 ± 0.08 | 100% | 6.35 ± 0.07 | 100% | 8.98 ± 0.11 | 100% |
| 1,000 | 1.38 ± 0.00 | 100% | 2.65 ± 0.03 | 100% | 4.18 × 0.05 | 100% | 5.82 ± 0.06 | 100% |



(a) up to 20%



(b) up to 5%, with fixed pulse range

Figure 4. Performance of swarm under communication loss.

## VII. DISCUSSION

The results show that a relationship may be established between the performance of the swarm and the pulse range used for transmitting the data, as seen in Fig. 2. This relationship is specific to the task employed, in this case the sharing of data to at least 99.5% of the swarm within 250 ticks. Different tasks, with different requirements for success, will necessarily result in a different relationship being established.

Increasing the pulse period has a detrimental effect on swarm performance, although it would reduce the energy used as fewer pulses would be sent. Balancing the performance needs of the swarm with the energy cost is an important factor, so a pulse period of 10 ticks was chosen for the adaptive APC and communications loss tests. Halving the period to 5 ticks would double the expected energy usage for only a small gain in performance, as seen in Fig. 3. Any performance decrease from using a longer period can be balanced through pulse range selection in the adaptive APC system.

The results in Table II show that the adaptive APC system, when starting with an initial pulse range of just one unit, is able to determine an appropriate range for a robot to broadcast at and enable the sharing of the data throughout the swarm within the allotted 250 ticks.

When comparing the average pulse range in Table II to the best fixed ranges in Table I, the adaptive APC system is found to have a slightly higher range on average in lower density swarms, but in higher density swarms it can reduce the average pulse range, allowing the swarm to expend less energy. In the more dense swarms, not every robot will detect the same local density, so the APC system enables the robots to reduce their pulse range while in higher density areas.

The APC system was also found to be extremely robust to communications loss, being able to successfully share the data within 250 ticks even when the probability of a successful message is as low as 5%, and it performs much better than the fixed pulse range at that level. A lower number of pulses being successfully received will result in a lower density estimate being made by the APC system, and a corresponding increase in the pulse range to reach more robots. While this system balances, increasing pulse ranges will increase energy usage.

It may be preferable for the swarm in cases of extremely high message loss to recognise the problem and find an alternative solution, perhaps contracting the swarm or temporarily increasing the period between pulses. Adaptive adjustment of the pulse period may help reduce energy usage overall, and this may be a topic for future work.

## VIII. CONCLUSION AND FUTURE WORK

This research presented a system for adaptively adjusting the range of communications between robots based on the density of the swarm, by adapting the existing concept of Pulse Monitoring. By replacing the “I am healthy” message with one saying “I am here”, a receiving robot can use the aggregate data presented by multiple received pulses to estimate the local density of the swarm.

In a task to share a piece of data with the rest of the swarm, the Autonomic Pulse Communications system was able to adaptively determine the pulse range to use to achieve excellent results, ensuring that 100% of the swarm received the data within the allotted time in all but three scenarios. The results show the system selecting shorter pulse ranges when the swarms are denser, and compare favourably with the best performing fixed pulse ranges used to establish the relationship between density and pulse range that the system uses. Further, the APC system was shown to be extremely robust to communications loss, as the system adapts to a decrease in the number of received messages by increasing the pulse range, thus increasing the chances of the message being received by some robots.

The APC system therefore shows promise, allowing a swarm to maintain communication links between its members while imposing fewer restrictions on the behaviour of the robots. Should the swarm suffer loss of robots over the course of the mission, the resulting lower density of the swarm may be compensated for automatically by the system.

Individual pulse messages used in this work were simplified, by considering them to be atomic actions. Larger amounts of data may take longer to broadcast than small packets, and this will impact the ability of a robot to successfully receive all of the data in a single broadcast. The motion of the robots may result in a recipient moving out of range before the transmission is completed. Additionally, communications failure was simply modelled as a random chance of failure, not taking into account the operating conditions or physical obstructions in the path.

Future work may investigate the impact of those aspects on the system, as well as applying the APC system in a more complex task, such as the foraging scenarios used in [8], or a collective decision-making task, where the data being transferred has a specific use that impacts performance of the wider task. Another avenue of interest may be the mechanism by which data is shared. As information grows in complexity, it may be desirable to selectively share only a portion of data in order to minimise the time and energy costs of data transfer, keeping the pulse messages short.

Further work may also investigate the impact of other factors in the ability of the swarm to share data. In this work, the data to be shared was fixed, so a changing data set that requires frequent reporting should be investigated. Also of note is the movement of the swarm, which supports data sharing through changing the set of neighbours receiving a robot's pulse. Different robot speeds, more limited mixing, and the absence of motion altogether may impact the performance of the system.

## REFERENCES

[1] E. Sahin, 'Swarm robotics: From sources of inspiration to domains of application', in *Swarm Robotics*, vol. 3342, E. Sahin and W. M. Spears, Eds. 2005, pp. 10–20.

[2] M. G. Hinchey, R. Sterritt, and C. Rouff, 'Swarms and Swarm Intelligence', *Computer*, vol. 40, no. 4, pp. 111–113, Apr. 2007.

[3] V. Trianni, J. IJsselmuiden, and R. Haken, 'The SAGA concept: Swarm Robotics for Agricultural Applications', Technical Report, 2016. Accessed: Dec. 21, 2022. [Online]. Available: http://laral.istc.cnr.it/saga/wp-content/uploads/2016/09/saga-dars2016.pdf.

[4] L. Abraham, S. Biju, F. Biju, J. Jose, R. Kalantri, and S. Rajguru, 'Swarm Robotics in Disaster Management', in *2019 International Conference on Innovative Sustainable Computational Technologies (CISCT)*, Oct. 2019, pp. 1–5.

[5] G. Beni, 'From Swarm Intelligence to Swarm Robotics', in *Swarm Robotics*, Berlin, Heidelberg, 2005, pp. 1–9.

[6] J. O. Kephart and D. M. Chess, 'The vision of autonomic computing', *Computer*, vol. 36, no. 1, pp. 41–50, Jan. 2003.

[7] E. Vassev, R. Sterritt, C. Rouff, and M. Hinchey, 'Swarm Technology at NASA: Building Resilient Systems', *IT Prof.*, vol. 14, no. 2, pp. 36–42, Mar. 2012.

[8] L. McGuigan, R. Sterritt, G. Wilkie, and G. Hawe, 'Decentralised Autonomic Self-Adaptation in a Foraging Robot Swarm', *Int. J. Adv. Intell. Syst.*, vol. 15, no. 1 & 2, pp. 12–23, 2022.

[9] M. Puviani, G. Cabri, and L. Leonardi, 'Enabling Self-Expression: The Use of Roles to Dynamically Change Adaptation Patterns', in *2014 IEEE Eighth International Conference on Self-Adaptive and Self-Organizing Systems Workshops*, Imperial College, London, United Kingdom, Sep. 2014, pp. 14–19.

[10] F. Zambonelli, N. Bicocchi, G. Cabri, L. Leonardi, and M. Puviani, 'On Self-Adaptation, Self-Expression, and Self-Awareness in Autonomic Service Component Ensembles', in *2011 Fifth IEEE Conference on Self-Adaptive and Self-Organizing Systems Workshops*, Ann Arbor, MI, USA, Oct. 2011, pp. 108–113.

[11] J. Zelenka, T. Kasanický, and I. Budinská, 'A Self-adapting Method for 3D Environment Exploration Inspired by Swarm Behaviour', in *Advances in Service and Industrial Robotics*, Cham, 2018, pp. 493–502.

[12] C. Saunders, R. Sterritt, and G. Wilkie, 'Autonomic Cooperation Strategies for Robot Swarms', in *Adaptive 2016: The Eighth International Conference on Adaptive and Self-Adaptive Systems and Applications*, Rome, Italy, Mar. 2016, pp. 20–27.

[13] G. Valentini, E. Ferrante, and M. Dorigo, 'The Best-of-n Problem in Robot Swarms: Formalization, State of the Art, and Novel Perspectives', *Front. Robot. AI*, vol. 4, 2017, Accessed: Jan. 03, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2017.00009.

[14] B. Capelli and L. Sabattini, 'Connectivity Maintenance: Global and Optimized approach through Control Barrier Functions', in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, May 2020, pp. 5590–5596.

[15] B. Capelli, H. Fouad, G. Beltrame, and L. Sabattini, 'Decentralized Connectivity Maintenance with Time Delays using Control Barrier Functions', in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, May 2021, pp. 1586–1592.

[16] Y. Kantaros, M. Guo, and M. M. Zavlanos, 'Temporal Logic Task Planning and Intermittent Connectivity Control of Mobile Robot Networks', *IEEE Trans. Autom. Control*, vol. 64, no. 10, pp. 4105–4120, Oct. 2019.

[17] N. Majcherczyk, A. Jayabalan, G. Beltrame, and C. Pinciroli, 'Decentralized Connectivity-Preserving Deployment of Large-Scale Robot Swarms', in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2018, pp. 4295–4302.

[18] V. S. Varadharajan, D. St-Onge, B. Adams, and G. Beltrame, 'Swarm Relays: Distributed Self-Healing Ground-and-Air Connectivity Chains', *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 5347–5354, Oct. 2020.

[19] P. Smith, R. Hunjet, A. Aleti, and J. Barca, 'Data Transfer via UAV Swarm Behaviours', *J. Telecommun. Digit. Econ.*, vol. 6, pp. 35–57, Jun. 2018.

[20] P. Gupta and P. R. Kumar, 'The capacity of wireless networks', *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[21] R. Sterritt, 'Pulse monitoring: extending the health-check for the autonomic grid', in *IEEE International Conference on Industrial Informatics, 2003. INDIN 2003. Proceedings.*, Banff, AB, Canada, 2003, pp. 433–440.

[22] R. Sterritt and S. Chung, 'Personal autonomic computing self-healing tool', in *Proceedings. 11th IEEE International Conference and Workshop on the Engineering of Computer-Based Systems, 2004.*, May 2004, pp. 513–520.

[23] R. Sterritt, D. Gunning, A. Meban, and P. Henning, 'Exploring autonomic options in an unified fault management architecture through reflex reactions via pulse monitoring', in *Proceedings. 11th IEEE International Conference and Workshop on the Engineering of Computer-Based Systems, 2004.*, Brno, Czech Republic, 2004, pp. 449–455.

[24] W. Truszkowski, M. Hinchey, and R. Sterritt, ‘Towards an Autonomic Cluster Management System (ACMS) with Reflex Autonomicity: Workshop on Reliability and Autonomic Management in Parallel and Distributed Systems (RAMPDS-05) at ICPADS-2005’, *Unkn. Host Publ.*, pp. 478–482, Jul. 2005.

[25] E. Vassev and M. Hinchey, ‘Self-Awareness in Autonomous Nano-Technology Swarm Missions’, in *2011 Fifth IEEE Conference on Self-Adaptive and Self-Organizing Systems Workshops*, Ann Arbor, MI, USA, Oct. 2011, pp. 133–136.

[26] K. Støy, ‘Using Situated Communication in Distributed Autonomous Mobile Robotics’, *SCAI*, vol. 1, pp. 44–52, Feb. 2001.