

DESIGN AND DEVELOPMENT OF A CARBON
DIOXIDE BASED PROPULSION SYSTEM FOR
FIREFIGHTING ROBOT

BY

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A thesis submitted in fulfilment of the requirement for the
degree of Doctor of Philosophy (Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

NOVEMBER 2021

ABSTRACT

Firefighters typically fight the fire from a safe distance for their protection, which contributes to inefficient firefighting operations. As a result, firefighting robots (FFRs) are integrated into firefighting tasks to increase firefighters' work performance. The power supply issue is one of the significant challenges when developing an FFR that operates in the real-life fire scenario. Electrically powered-dc motors (DCPM) are the most common power sources utilized for the mobility of the FFRs. However, the DCPM performance is unreliable in a high-temperature environment that characterizes a real-life indoor fire emergency. Therefore, this study aims to develop a carbon dioxide (CO₂) gas based propulsion system for FFR application. The CO₂ gas based propulsion system (CO₂_PROS) is composed of a pneumatic (air) motor and a CO₂ gas-power source. The pneumatic motor is used as the actuator for the FFR system, while the CO₂ gas (instead of the conventional 'air') generated *in-situ* from dry ice within the robotic system is used as the power source. The mass of dry ice (M_{Di}), is computed analytically using a governing equation that was based on the ideal gas equation. With an air motor consumption requirement of 33 lpm, an operating time of five minutes, and supply pressure to the air motor ranging from 14 psi to 22 psi, a volume of 165 liters was computed as the required volume to efficiently power the proposed carbon dioxide gas propulsion system for a selected FFR operating time. Previous studies that used the phase change of carbon dioxide are limited to generating a high volume of CO₂ gas from dry ice without reference to the production rate of the gas. Thus such consideration remains a design requirement for the efficient driving of a FFR. Based on the limited data on the sublimation rate (SR) of dry ice, hot water is used as a catalyst in this research. An experimental approach was employed to examine the design parameters to investigate their effects on the system responses. Using a design of experiment technique, a full-factorial design along with response surface methodology approaches, M_{Di} and water temperature (T_w) were identified as the two influencing variables on the SR of dry ice. The results obtained showed that higher T_w and M_{Di} leads to increased SR, with M_{Di} having a higher effect on the SR. An optimal SR of 0.1025 g/s was obtained at a temperature of 80 °C, mass of 16.1683 g, and sublimation time of 159.375 s. A prototype of the CO₂_PROS power source, which is known as the dry ice power chamber (DiPC), was designed and prototyped in this study. An experimental test rig that integrates TONSON air motor with a prony brake arrangement was utilized to examine the functionality of the prototyped DiPC. The air motor was powered with the generated *in-situ* CO₂ gas and air at different periods. The performance of the air motor, using air and CO₂ as fluid media, was analyzed using the mechanical power output (P_{out}) and efficiency produced by the air motor. The results showed that the P_{out} of the air motor demonstrates the same trend when using air or CO₂ gas as its power source. In both cases, P_{out} rises as the pressure increases when the torque is kept constant. The result obtained is significantly lower than the estimated result of 110 W, because the air motor did not perform as per the specification on its nameplate. This study, however, established the use of CO₂ gas power source in firefighting robots. An air motor with less internal losses could be used to achieve the expected power.

خلاصة البحث

في العادة، يواجه رجال الإطفاء النار عن بعد لحماية أنفسهم، مما يقلل من فاعلية عمليات مكافحة الحرائق. ونتيجة لذلك، يتم دمج روبوتات الإطفاء في مهام مكافحة الحرائق من أجل رفع مستوى الأداء. وتعدّ مسألة إمداد الطاقة من أبرز التحديات عند تطوير روبوتات الإطفاء التي تعمل في سيناريو الحريق الحقيقي. كما تعدّ محركات التيار الكهربائي المستمر من أكثر مصادر الطاقة شيوعاً واستخداماً في تنقل روبوتات الإطفاء. ومع ذلك، فإن أداء محركات التيار الكهربائي المستمر لا يمكن الاعتماد عليه في بيئة ذات درجة حرارة عالية، كالتي تميز حالة الطوارئ الناتجة عن الحريق داخل المباني. لذلك، تهدف هذه الدراسة إلى تطوير نظام دفع يعتمد على غاز ثاني أكسيد الكربون لتشغيل روبوتات الإطفاء. يتكون نظام الدفع المعتمد على غاز ثاني أكسيد الكربون من محرك بالهواء المضغوط ومصدر طاقة يعتمد على غاز ثاني أكسيد الكربون. حيث يستخدم محرك الهواء المضغوط كمصدر لنظام روبوتات الإطفاء، بينما يستخدم غاز ثاني أكسيد الكربون (بدلاً من الهواء الطبيعي) الناتج من الجليد الجاف داخل نظام الروبوت كمصدر للطاقة. يتم حساب كتلة الجليد الجاف تحليلياً باستخدام معادلة تحكم تستند إلى معادلة الغاز المثالي. مع متطلب استهلاك للمحرك الهوائي بمقدار 33 لتر في الدقيقة، ووقت تشغيلي خمس دقائق، وإمداد ضغط للمحرك الهوائي يتراوح بين 14 إلى 22 باوند للبوصة المربعة، تم حساب الحجم المطلوب للتشغيل الفعال للروبوت المقترح لمكافحة الحرائق لدفع ثاني أكسيد الكربون ومقداره 165 لتر. إن الدراسات السابقة التي استخدمت التغيير المرحلي لثاني أكسيد الكربون مقتصرة على توليد كمية كبيرة من غاز ثاني أكسيد الكربون من الثلج الجاف دون الإشارة إلى معدل إنتاج الغاز. وبالتالي، يظل هذا الاعتبار أحد متطلبات التصميم للتحريك الفعال لروبوت مكافحة الحرائق. وبناءً على محدودية البيانات حول معدل التسامي للجليد الجاف، تم استخدام الماء الساخن كعامل مساعد في هذا البحث. كما تم استخدام منهج تجريبي لفحص عوامل التصميم للتحقق من تأثيرها على استجابات النظام. وباستخدام تقنية تصميم التجربة، وتصميم كامل العوامل، إضافة إلى منهجية سطح الاستجابة، تم تحديد كتلة الجليد الجاف ودرجة حرارة الماء كمتغيرين مؤثرين على معدل التسامي للجليد الجاف. أظهرت النتائج التي تم الحصول عليها أن زيادة درجة حرارة الماء وكتلة الجليد الجاف يؤدي إلى زيادة معدل التسامي، في حين أن كتلة الجليد الجاف لها تأثير أكبر على معدل التسامي. وقد تم الحصول على معدل التسامي الأمثل 0.1025 غم/ثانية، عند درجة حرارة 80 درجة مئوية، وكتلة 16.1683 غم، ووقت تسامي 159.375 ثانية. في هذه الدراسة، تم تصميم نموذج أولي لمصدر طاقة للروبوت المقترح لمكافحة الحرائق، يعرف باسم حجرة طاقة الجليد الجاف. حيث تم استخدام جهاز اختبار تجريبي يدمج بين محرك (تونسون) الهوائي مع نظام فرامل (بروني) لفحص وظائف نموذج حجرة طاقة الجليد الجاف المقترحة. تم تشغيل المحرك الهوائي بوساطة غاز ثاني أكسيد الكربون المتولد والهواء في فترات مختلفة. تم تحليل أداء المحرك الهوائي، باستخدام الهواء وثاني أكسيد الكربون كوسط مائع، باستخدام ناتج الطاقة الميكانيكية والكفاءة التي ينتجها المحرك الهوائي. وتشير النتائج إلى أن ناتج الطاقة الميكانيكية للمحرك الهوائي يظهر الاتجاه نفسه عند استخدام الهواء أو غاز ثاني أكسيد الكربون كمصدر للطاقة. ففي كلتا الحالتين، يرتفع ناتج الطاقة الميكانيكية مع زيادة الضغط عندما يكون عزم الدوران ثابتاً. والنتيجة التي تم الحصول عليها أقل بكثير من النتيجة المتوقعة وهي 110 واط، وذلك لأن محرك الهواء لم يعمل وفقاً للمواصفات الموجودة على لوحة التعريف الخاصة به. ومع ذلك، فقد أسست هذه الدراسة لاستخدام غاز ثاني أكسيد الكربون كمصدر طاقة في روبوتات مكافحة الحرائق. ويمكن استخدام محرك هوائي ذي خسائر داخلية أقل لتحقيق الطاقة المتوقعة.

APPROVAL PAGE

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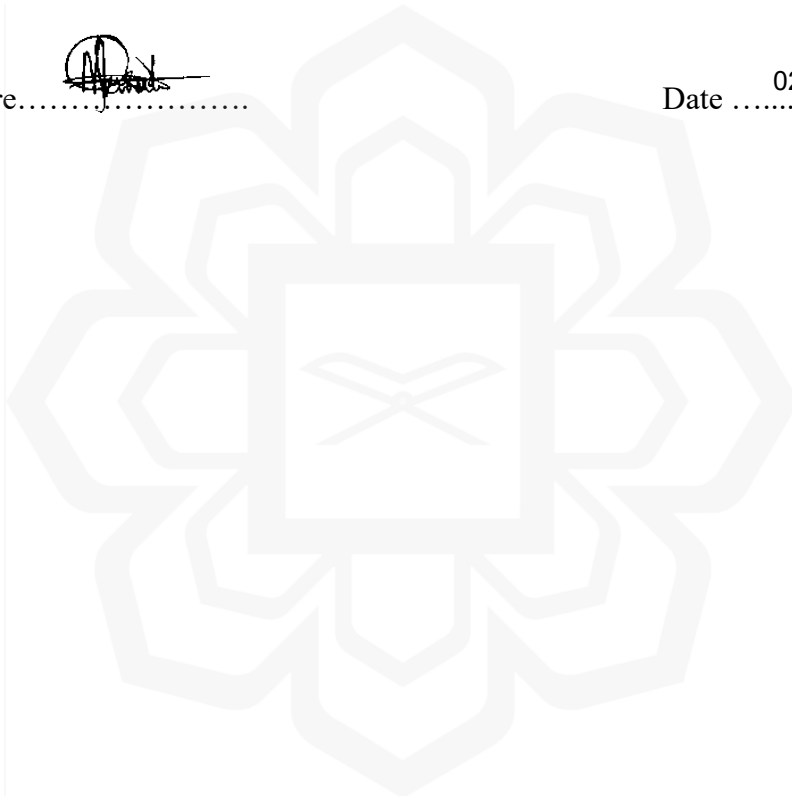
DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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DEDICATION

To my late parents, Mr AbdurRasheed and Mrs Silifat

To my late sister – Madinat I. Ajala

To my late wife – Kafayat O. Akinbola,

To my dearest wife – Kafayat Olabisi Makinde,

To my children (The Special Girls) – Khadeejah, Aasiyah, Maryam & Faatimah, and

To my Siblings

ACKNOWLEDGEMENTS

Praise be to Allah SWT, Who from His infinite mercies has given me the strength and ability to undertake this research.

First and foremost, I would like to express sincere thanks to my supervisor, Professor Md. Raisuddin Khan for his continuous support, encouragement, guidance and leadership. Also, I would like to thank my supervisory committee members; Prof MJE Salami and Prof Amir. A. Shafie, Mr Mohamad Nor, M. I., for their unwavering supports and their criticism of the research.

My appreciations also go to all my lecturers during the course of study at the International Islamic University Malaysia. You are people out of many to whom I remain grateful forever. Thank you all.

I wish to express my appreciation and thanks to those who provided their time, effort and support financially and otherwise for this research; Dr Maizirwan, Dr Khameel Mustapha, Zakat and Sodaqat, Saheed Adeleke, Engr Faheed , Engr Alao, Dr Nwosu, IME Staffs, Mr Ogunsanwo, Mr O.T. Raheem, Mr Shokunbi, Mr Salman Saheed, Editor, Mufty and Family, Shokunbi Abu umar, Barr SofiyuLlah, Mr and Mrs Anjorin, Mr and Mrs Afenifere, Mr Tajudeen Olawuyi, Mr and Mrs Jamil, Dr Afzal, Dr and Mrs Adesina, Queen Balqis, Mr Pedro A. Mr and Mrs Yusuf, Dr Misjudeen and Sis Muslimah, Laide Adekunle, The Okubadejos, Mr Olawuyi, Dr and Mrs No Shaking, The Adelus, The Tellas, BIS, Dr. Onasanya, My Bros in Malaysia and host of others.

I have benefitted greatly from the comments and suggestions of Dr Bunyamin, Mufti, Dr 'Laide, Assoc. Prof Rashidah O. O., Dr Oloketuyi, Engr. Ize-Balogban, Engr. (Dr.) I. Badmus and Engr. (Dr.) I. Abdul, I say thank you for being there.

My appreciation also goes to the members of staff of the Central Workshop – IIUM, staffs of the project development LAB, staffs of mechatronics workshop, and brother Muhammad Nuh.

I am indebted to all other benevolent individuals, who are numerous to mention. Allah knows everybody's effort to ensure the success of this study. There is no amount of words that can explain everything all of you have done for the actualisation of this academic sojourn. What else can I say unto you all...? *Jazakumullahu khayran Jaza'!*

Finally, to my loving wife, Alhaja Kafayat Olutomilola Omolara Olabisi Makinde, and children, Big Sister Khadeejah Oreoluwa Masud Ajala, Aasiyah Atinuke Feyi Masud Ajala (Yellow Malaysia) and Maryam Omolara Mosud Ajala for their patience, understanding and supports while away for the pursuit of this study. Also to my siblings, Engr. Atitebi, Engr. Oseni, FOREVER Living Family and my in-laws, who had to bear with the vacuum of coping with my absence. Thanks to you all.

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LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
ACSR	Ants based control of Swarm Robots
AFFMP	Autonomous Firefighting Mobile Platform
ANOVA	Analysis of variance
ANSF	Ant System with Negative Feedback
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CO2_PROS	CO2_ROB propulsion system
CO2_ROB	Carbon dioxide propelled autonomous firefighting robot
CO2_ROBP	CO2_ROB platform
DC	Direct Current
DCPM	DC powered-motor
DiC	Dry ice Chamber
DiPC	Dry ice Power Chamber
DOE	Design of Experiment
FA	Force required to accelerate to a final velocity.
FFD	Full-Factorial Design
FFR	Firefighting Robot
FFRs	Firefighting Robots
FFS	Firefighting systems
GR	Force required to climb a grade;
Grp	Group
ID	Internal Diameter
IR	Infrared Sensors
LASE	Low-Altitude, Short-Endurance
MANET	Mobile Ad Hoc Networking
MEMS	Micro-Electromechanical Systems
MSSS	Multi-spectral sensor system
NFPA	National Fire Protection Agency

NPS	Nominal Pipe Size
P	Pipe
PCM	Phase Change of Materials
RR	Force necessary to overcome rolling resistance
RSM	Response Surface Methodology
S/S	Stainless steel
SCH	Schedule
SF	Factor of safety
SR	Sublimation Rate
ST	Sublimation Time
TEG	Triethelyne Glycol
TOA	Taguchi Orthogonal Array
TOD	Task Oriented Design
TP	Type
TTE	Total Tractive Effort
UAVs	Unmanned aerial vehicles
UCFFR	Upward climbing firefighting robot
UTS	Ultimate Tensile Strength
W	Watt
WC	Water Chamber
WHPS	Water hydraulic-powered propulsion system
WLD	Welded
WNRF	Weld Neck Raised Face

LIST OF SYMBOLS

a_0	Intercept
a_i	Coefficient of linear factor effects
a_{ii}	Quadratic coefficients
a_{ij}	Interaction coefficient
a	Lid radius (mm)
A_t	Area of door opening (m ²)
A_t	Total internal surface area of the office room (m ²)
A_v	Area of door opening (m ²)
A	Pipe cross sectional area
c	Sum of mechanical allowance
$C_5F_{11}NO$	PerfluoroCarbon
CO_2	Carbon dioxide gas
C_R	Consumption rate (lpm)
$C_{R(\text{measured})}$	CO_2 volume flow rate measured by the NBDC flow meter
$C_{R(\text{actual})}$	Actual CO_2 volume flow rate
C_{rr}	Surface Friction
D_f	Internal diameter of the pipe/flange
D_i	Internal diameter (mm)
D_o	Outside Diameter (mm)
D_p	Internal diameter of the pipe/flange
D	Internal diameter of the pipe/flange
D	Room depth (m)
E	Quality factor
E	Modulus of Elasticity
E_f	Fire load (MJ)
e_f	Fire load density (MJ/m ²)
E_s	Endurance Strength
h	Lid thickness (mm)
h	Overall height of the pressure chamber
h_f	Flange Height
H_v	Door Height (m)

H	Total height (m)
l_1	Room length (m)
l_2	Room width (m)
l_3	Room height (m)
L_p	Length (mm)
L_p	Pipe Length/Height;
\dot{m}	Rate of burning (kg/s)
\dot{m}_{air}	Mass flow rate of air (kg/s)
m	Mass (g)
M	Molar mass of carbon dioxide gas
M_{Di}	Mass of dry ice (g)
M_{req}	Required mass of dry ice (kg)
n	No of moles (mol)
p	Pressure (psi)
p_d	Design Pressure (psi)
p_{relief}	Relief Pressure (psi)
p_{safe}	Safety Pressure (psi)
p_{wmax}	Max Working Pressure (psi)
p_{wmin}	Min Working Pressure (psi)
P_{in}	Power input (W)
P_{out}	Power output
$P_{in(fluid)}$	Fluid power required by the actuator
$P_{in(robot)}$	Mechanical power required by the robot
$P_{out(actuator)}$	Mechanical output power from the actuator
Q_{AVE}	Average volumetric flow rate (lpm)
Q_{air}	Volume flow rate of air (lpm)
Q_{CO_2}	Volume flow rate of CO ₂ (lpm)
R_f	Resistance factor
R	Radius of the platform wheel
R	Universal gas constant,
S	Allowable stress for the material selected
t_m	Minimum required thickness
t	Second (s)
t	Thickness (mm)

t_b	Burning time (s)
T	Temperature (K)
T_w	Water temperature ($^{\circ}\text{C}$)
T	Torque required to move the mobile robot
v	Velocity (m/s)
v_{air}	Air velocity
v	Fluid velocity (m/s)
V	Volume of the pressure chamber;
V_{opt}	Volume of the pressure chamber
V_{co2}	Volume of CO_2 gas required to power $\text{CO}_2\text{-ROB}$
W_d	Door width (m)
w_{max}	Maximum deflection (mm)
w_{ave}	Average rotational speed (rpm)
W_{PC}	Overall weight of the pressure chamber
W_r	Weight of Robot (kg)
W	Welding joint reduction factor
w	Angular Speed (rad/s)
X	Control factors
X_1	Water Temperature ($^{\circ}\text{C}$)
X_2	Mass of Dry ice (g)
Y	Wall thickness correction factor
Y_1	Sublimation rate (g/s)
Y_2	Sublimation time (s)
Y	Response
ΔH_c	Heat of combustion of firewood (MJ/kg)
Δp	Pressure difference (Pa)
ϵ	Error terms
γ_{CO_2}	CO_2 gas specific gravity with respect to air
Ω	Opening factor
ρ	Fluid density (kg/m^3)
ρ_{air}	Air density (kg/m^3)
σ_{max}	Maximum stress (ksi)
σ_w	Working stress limit (MPa)

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

1.1.1 Firefighting

Fire is a friend but turns a foe when uncontrolled. It becomes a disaster marked by heavy human and financial losses (Shah, Shah, Mamtora, & Hapani, 2013), pollution, oxygen-deficient environment, and elevated temperature when not controlled well. Besides damage to life and property, firefighters are also prone to dangers owing to the high temperature of the fire environment.

Consequently, firefighters sustain injuries such as burns, smoke and gas inhalation, cut, heart attack, and thermal stress (Alan, 2011; McNeil & Lattimer, 2016). Lack of details on information about the victims trapped in the fire and the situation in the fire zone increases the risk to firefighters (Casbeer, Beard, McLain, Li, & Mehra, 2005; Chang, Kang, Cho, Kim, Jin, Lee, Jeong, Han, Jung, & Lee, 2006). Statistical analysis of firefighters' injuries and deaths reveal that 58,250 firefighter injuries occurred during the year 2018 (Campbell & Molis, 2019). Out of this figure, approximately thirty-nine percent of these injuries ensued from fire ground operations. Firefighting, therefore, poses a high risk of personal injury to firefighters.

Conventionally, there are two methods of firefighting, namely, passive and active methods. The passive technique involves the creation of compartments in the design of the buildings, using fire-resistant materials such as concrete, fire-resistant doors, and so on. This method is mainly to contain the fire from spreading. The active approach makes use of devices such as portable fire extinguishers, fire hydrant and hose

reel system, wet and dry riser system, down-comer system, automatic sprinkler system, automatic carbon dioxide extinguishing system, heat detectors, smoke detectors, flame detectors, infrared barriers, manual station, and gas detectors, for extinguishing fire. Nevertheless, firefighters are still exposed to dangers during firefighting missions. They work around a high temperature that ranges between 250 °C and 1500 °C, for a period which is known as “*flash over*” period in firefighting. The firefighters lack detailed information about the victims trapped in the fire and about the situation in the building. Sometimes this is caused by heavy smoke that leads to poor vision (Casbeer et al., 2005; Chang et al., 2006). Consequently, the firefighters could as well become fire victims, and as such, firefighting presents great risks of personal injury to firefighters.

1.1.2 Mobile Robot Technology into Firefighting

The introduction and integration of mobile robots into firefighting tasks was developed to lessen injuries of firefighters and increase their work performance, with a primary objective of supporting and replacing the firefighters (Okada, 1988; Amano, 2002; Saravanan, 2015). Hence, the birth of the firefighting robot (FFR) and quests to develop FFR systems.

FFR technology research started around the early ‘80s. Research during the period inclined towards: justifying the need for an FFR, figuring out the concept that the FFR would assume (fixed, mobile, humanoid, snake robot locomotion) and specifying the requirements for the performance of the FFR. All of these can be summarized to include need identification, concept development, and the performance requirement specification. For example, the study of Poole (1989), one of the earliest research work in FFR developments, suggested firefighting tasks as one area of

application of robotic technology. Also, Todd (1985) conceived a walking locomotion concept for robots in firefighting applications. McCloy and Harris (1986), in their study, specified the ability to enter a fire hot spot as a performance requirement for any FFR. Following the performance specification by McCloy and Harris (1986), Okada (1988) recommended the ability to survive under a temperature of 400 °C for 30 minutes or 880 °C for 3 minutes as a performance requirement for FFR developed in Japan at that time.

FFRs have been studied extensively with wide areas of application covering use in high-rise building fires (Amano, Osuka, & Tarn, 2001; Jiang, Luo, & Li, 2013; Gomez, Matson, Song, Baek, & Kim, 2015; Alshbatat, 2018; Liu & Hu, 2019), tunnel fire (Siciliano & Villani, 2004; De Santis, Siciliano, & Villani, 2005; Celentano, Siciliano, & Villani, 2005; De Santis, Siciliano, & Villani, 2008), petrochemical industry fire (Lufeng & Daoling, 2002; Kim, Keller, & Lattimer, 2013; Varghese, Paul, George, Ali, & Warier, 2018), security in an intelligent building (Park, Kim, Park, & Kim, 2008; Sonsale, Gawas, Pise, & Kaldate, 2014), teaching and education demonstrations (Seng, 2003; Reinhart, Khandwala, Shah, Young, Ross, Delica, Angus, Burford, Lynch, & Pollard, 2003; Miller, Rodriguez, Allen, Makeev, Plew, & Schwartz, 2003; Dubel, Gongora, Bechtold, & Diaz, 2003; Altaf, Akbar, & Ijaz, 2007; Bao, Zhang, Wang, & Hu, 2007; Zhao, Tan, Wen, & Guo, 2008). Given the diverse application areas, FFR can be classified (see Figure 1.1) by its:

- Operating environment
- Mode of operation, and
- Task performed

Going by the operating environment, a literature search revealed that FFRs are found applicable in the indoor and outdoor environments. Thus, FFRs can be classified