Shipboard Intelligent Fire Suppression Systems

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1 Introduction

The fire risks associated with the environment of a naval ship's machinery space are well understood but nevertheless present some particularly problematic issues for the design and implementation of detection and suppression systems. These problems are exacerbated where the preservation of operational capability is important such as on a naval fighting platform.

In these environments, fires are likely to be instantaneous and large in magnitude. By the time they are detected and acted upon much, if not all of the enclosure's contents may be damaged by the fire or the extinguishing process employed and significant capability lost. Royal Navy (RN) ship design incorporates measures to limit the loss of capability by duplicating assets in mirrored compartments; protection of some compartments with fixed systems; and extensive crew competency in managing fires once detected, but most of these measures are reactive and, given the nature of the likely fire scenarios inherently accept considerable levels of damage.

Recent improvements in ship design and technology have led to greater optimisation in manning in the areas of operation and maintenance, however the corresponding advances in fire protection and suppression have been limited and the RN remains heavily dependent on manual response and intervention to fire incidents. The equipment and techniques used by the Royal Navy for firefighting today are tried and tested but have been in service for over thirty years and their relevance may expire in due course. The reasons for this are many and varied but include: leaner manning; larger platforms; greater platform design complexity; fewer platforms and a greater emphasis on employee health & safety, and incident costs. If no mitigating actions are taken a worst case future scenario may involve fewer RN vessels that are: very expensive; of increased strategic importance; have higher utilisation and are unsuitable for the implementation of historically used fire fighting practices yet, will have a lower manual fire-fighting & detection capability and more onerous H&S requirements to meet in terms of crew well being.

To address these issues MOD's MESH Fire Safety commissioned work to develop a system capable of rapid, if not predictive, detection ability that can automatically initiate efficient fire suppression measures. The project was entitled "Shipboard Intelligent Fire Suppression Systems", or SIFSS, and this paper describes briefly the ambition and in particular, investigations into two mechanisms for the automatic location and sizing of fires to an accuracy appropriate for instructing a robotically aimed low consequence suppression system. Elements of the project dealing with the integration of data and detailing of the logic trees to provide the response most appropriate to the ship's circumstance will be the subject of further papers. Participating in this study has been the Fire Protection Association, BAE Systems, and Rolls-Royce.

2 The SIFSS process

In current RN firefighting practice 1st aid manual intervention represents the response with the lowest consequential damage and SIFSS' ultimate goal, leaving aside the predictive element, must be to provide a response akin to that provided by a man with an extinguisher at the location of the event at the earliest possible moment after ignition. A man with an extinguisher has the ability to aim the discharge and decide when enough extinguishant has been deployed; a truly proportional response. Whilst there are many exciting new suppression systems on the market that could provide the extinguishing performance required with very low suppressant usage it is clear that currently employed detection systems are a long way off being able to support fire tracking and fire size estimation with the required accuracy.

The primary elements of the envisaged SIFSS are:

- Early and reliable detection of a fire – ideally predictive
- Location of the seat of fire
- A degree of measurement of the fire (i.e. size, type, life-cycle position)
- Capability to 'prepare' the enclosure for optimal attack – control of fuel, oxygen, and ignition sources
- Initiation of a proportional fire fighting response to the fire in terms of, area of operation, weight of attack, and extinguishing system selection
- Protection of adjacent spaces and preservation of operational capabilities
- Re-entry monitoring (firefighter safety)
- Capability to continuously reconsider actions in accordance with availability of systems.

- Capability to reconfigure actions, responses and level of automation in accordance with the 'ship's state'

By centralising all ship's system data on the Platform Management System (PMS) the response most appropriate to the ship's immediate circumstance may be selected quickly and efficiently. Ideally, initiation of a suitable preventative response will take place within 180 seconds of first notification.

3 Fire event life-cycle & selection of appropriate measurement parameters

To determine the requirements of the sensor suite in relation to fulfilling the SIFSS ambition it is important to consider the life cycle of a typical failure event in respect of what parameters are present to be measured at any given time.

Figure 1 illustrates a typical failure sequence of mechanical equipment. Under normal conditions there is obviously nothing anomalous to detect. As the involved apparatus deteriorates with use it may undergo changes that are measurable, but not necessarily by any specific fire detection equipment, such as vibration, excessive noise, reduced efficiency, increased bearing temperatures etc. which may eventually lead to a fire. The majority of these scenarios are avoided by maintenance and equipment replacement programmes, but not all. Action on these parameters obviously represents the earliest possible opportunity to avoid a fire incident but does require significant investment in equipment telemetry which will be diverse in nature and potentially great in quantity.

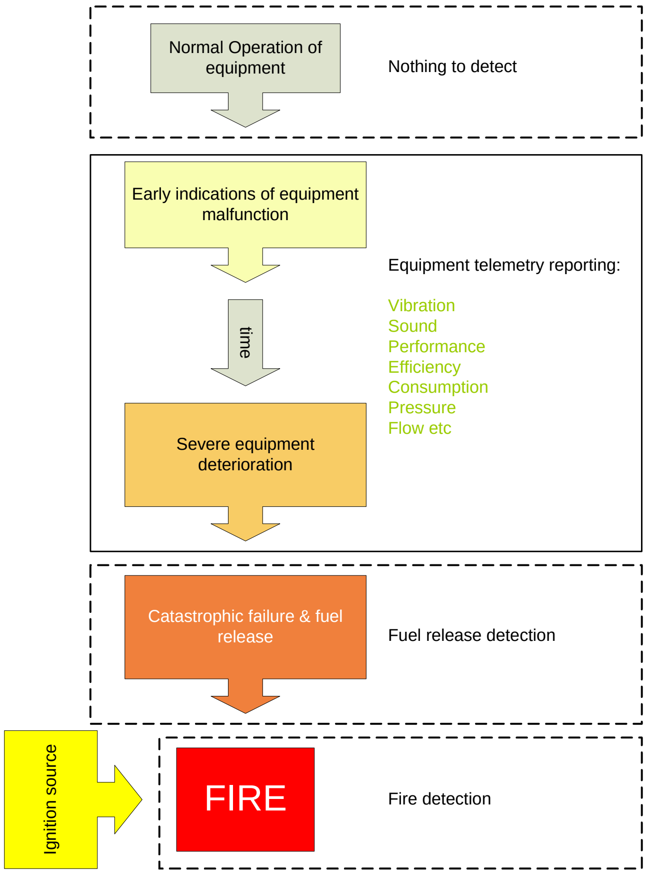


Figure 1 - Example of failure sequence for mechanical equipment

Following further deterioration an element of the equipment may fail resulting in fuel release. Characteristics associated with fuel, lube oil and hydraulic oil release may include sound, vapour, particulate mists and smoke and the presence of these substances in places where they should not otherwise be. Whether these can be detected in isolation from the fire depends upon the nature of the release and the proximity of ignition sources. Obviously, once ignited, the fire, and all of its fingerprint characteristics are present to be detected.

Whilst there are many parameters associated with fire that can reliably (in combination) be used for detection purposes, few parameters are capable of describing the fire's size, growth and location. Practical measurements are limited to the estimation of heat output by temperature, or spectral emissions (Visible/IR/UV) – oxygen depletion, such as might be used in calorimetry, being too complex in these uncontrolled conditions. The environment in which these parameters are to be measured must also be carefully considered with the key factors being:

- Amount of enclosure ‘clutter’ – suitability to accommodate line-of-sight type device
- Deckhead height – communication with the fire plume / fire products
- Degree of ventilation and level of control – dilution and diversion of fire products

In the context of this work the following environments were considered:

Ship’s space	Characteristic
Ship’s machinery space	• High levels of ‘clutter’ (poor lines of sight) • relatively low ceiling heights • ventilated by controllable systems
Vehicle or hangar deck	• Variable levels of ‘clutter’ • high deckhead heights • uncontrolled ventilation

In this study the first three detection modes; equipment malfunction; fuel release, and fire, may be considered to use commonly available equipment. For the location and sizing of the fire deckhead temperature mapping is considered the most appropriate option for the cluttered confines of the machinery space, and video fire location considered best suited to the relatively open areas of hangar and vehicle decks.

Experiments investigating these techniques are outlined below.

4 Fire location by deckhead temperature mapping

To support SIFSS, thermal mapping of the deckhead would be used in conjunction with other detectors (fire and precursor) to maximise the speed and accuracy of response to the incident.

As described in Figure 1 temperature mapping alone might achieve:

- Early fire detection through accurate temperature measurement against a pre-defined threshold
- Fire location through identification of peak temperatures
- Fire sizing through identification of ‘areas’ above a predefined threshold value
- Fire growth through evaluation of peak temperatures and temperature area thresholds over time

The thermal mapping of large surface areas at the resolution required to support SIFSS would generally require great numbers of point detectors which would be expensive in terms of:

- Cost of purchase
- Installation complexity
- Maintenance
- PMS burden

Linear detection systems have been employed for many years in the marine environment but the majority of these are incapable of resolving the position of the fire incident except on a zone by zone basis. However, new fibre optic based technologies are capable of resolving temperatures over very great areas using a single device and instruments such as this offer the potential for the development of new fire characterisation techniques.

The chosen apparatus for quantifying the fire in the machinery space scenario is Fibre Temperature Radar (FTR). It consists of an electronics interface box, laser and computer at the user end, connected to a single length of optical fibre that may typically be up to 10km in length which for this application would be distributed over the surface to be measured. Temperature readings are typically measured along the fibre to a spatial resolution of 1 m and resolution of 1^{o}C at a refresh rate of around 7 seconds.

FTR uses Raman frequency analysis of back-scattered laser light from the bulk of the optic fibre. The back-scattered light from a laser pulse is optoelectronically analysed and the ratio of stokes to anti-stokes light intensity is used to calculate the temperature of the material that scattered it. The location of the measured temperature is obtained from measuring the time delay between signal delivery and return.

However, unless special provisions are made it would be wrong to assume that FTR is equivalent to locating a thermocouple every meter along the route of the fibre optic cable. To record the applied temperature requires a significant length of cable to be heated which, in the case of normal 1 mm nylon coated communications cable (See Figure 2) is around 2 to 3 metres. Lengths shorter than this report lower temperatures and will never achieve the applied value. Where recognition of true values is important at point locations it is possible to coil the fibre into 'bunches' which will report more accurately. The thermal response of the cable is shown in Figure 3

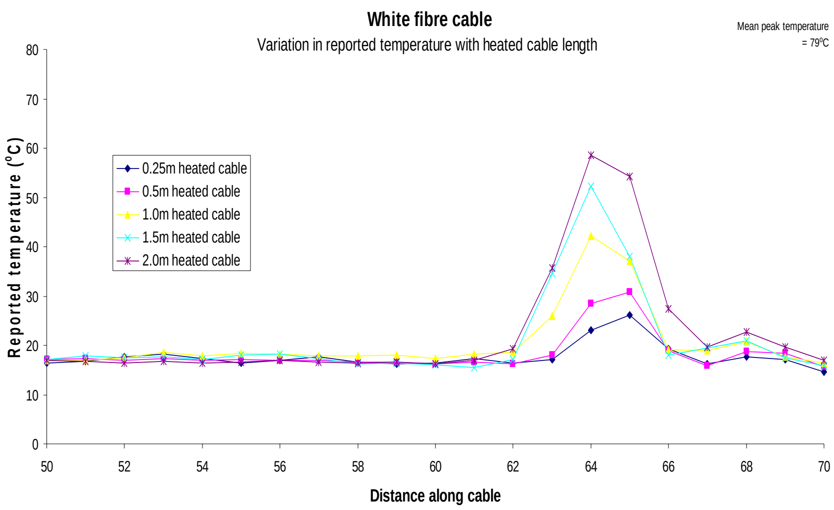


Figure 2 - Effect of heated length of cable on reported temperature

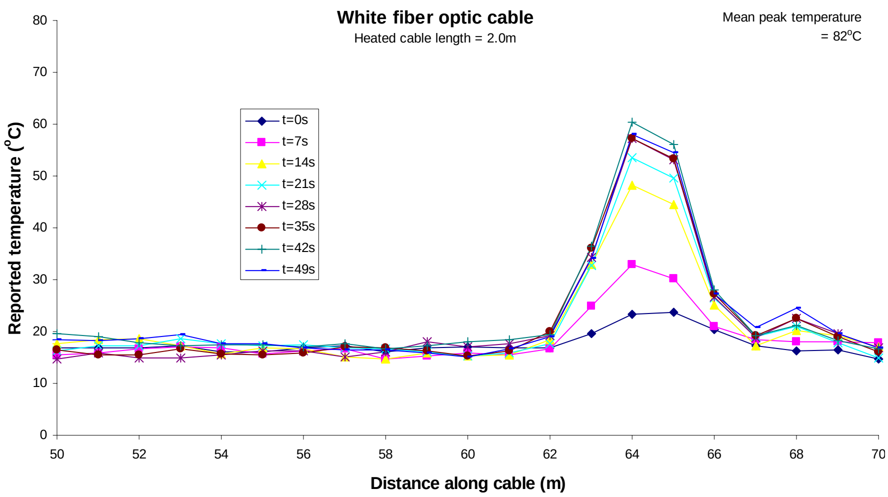


Figure 3 - Response time of 2.0m heated cable

Whilst the use of FTR was evaluated in this study at small scale, evaluation of the potential of surface temperature mapping to support the SIFSS concept was performed using large numbers of type K thermocouples. Thermocouples are more reliable than the somewhat 'aged' FTR system that was available to the project and more suited to the repeated abuses of the test programme.

Ceiling temperature mapping was achieved using an array of 210 thermocouples attached to the underside of a 7 m by 7 m test rig ceiling arranged in a square grid matrix of 0.5m spacing (see Figure 4 and Figure 5).

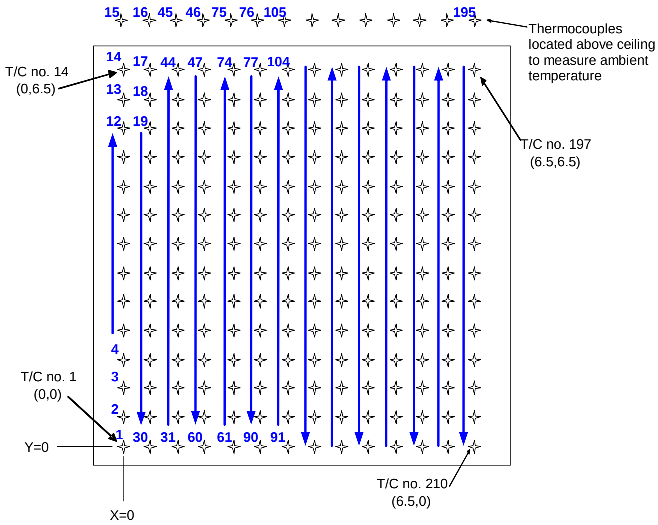
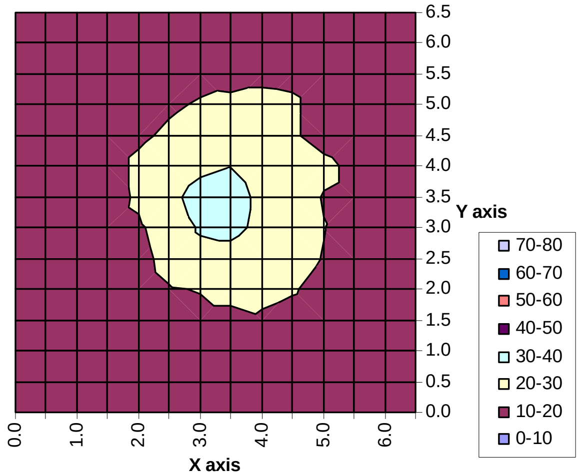


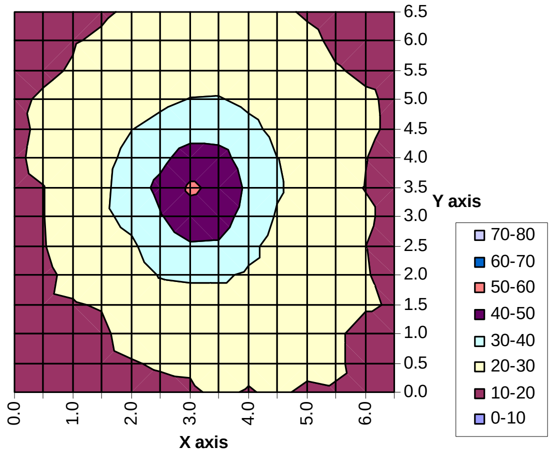
Figure 4 – Thermocouple location on the test ceiling

Figure 5 – The test ceiling

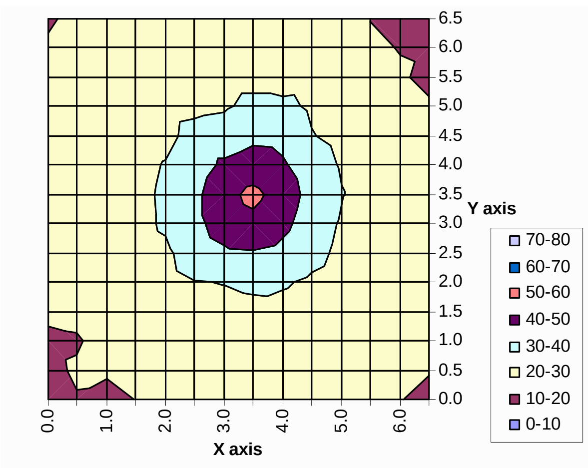
Figure 6 to Figure 8 show thermal maps taken over a period of 3 minutes for a 50 kW fire, 150 kW fire, and 100 kW baffled fire (significant baffle under ceiling), respectively. Using a threshold temperature of 50°C, fire detection and location capability for each of these fires is established in Table 1 to Table 3. The true position of the fire in each test was x=3.25m and y=3.25m.



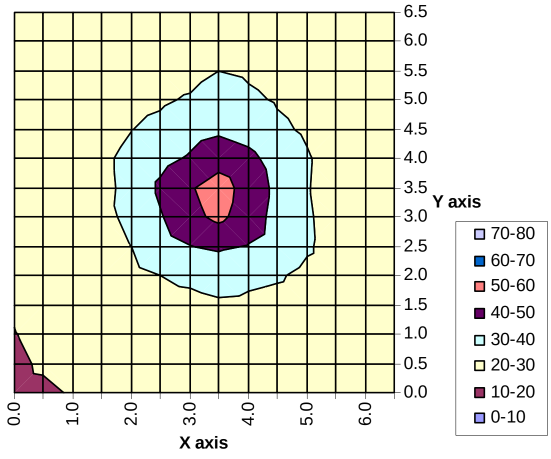
12 seconds



37 seconds



73 seconds



159 seconds

Figure 6 – Temperature maps from a 50 kW fire 3.5 m below the ceiling

Test 17 50kW (3.25,3.25)

Time	Peak	Area above	Peak temp location		Estimated fire location	
(sec)	Temp	threshold (m2)	X	Y	X	Y
-12	11.7	0.0	N/A	N/A	N/A	N/A
0	11.7	0.0	N/A	N/A	N/A	N/A
12	33.7	0.0	3.25	3.25	N/A	N/A
25	43.7	0.0	3.25	3.50	N/A	N/A
37	51.6	0.3	3.25	3.25	3.00	3.00
49	51.8	0.5	3.25	3.25	3.25	3.25
61	53.4	0.5	3.38	3.50	3.25	3.25
73	52.5	0.3	3.50	3.38	3.50	3.50
86	54.7	0.5	3.25	3.25	3.50	3.50
98	55.9	0.5	3.25	3.25	3.25	3.25
110	53.3	0.5	3.25	3.75	3.25	3.25
122	51.0	0.5	3.25	3.25	3.25	3.25
135	52.5	0.5	3.25	3.25	3.50	3.50
147	54.1	0.5	3.25	3.25	3.50	3.50
159	54.4	0.5	3.25	3.25	3.50	3.50
171	55.2	0.5	3.25	3.25	3.50	3.50

Max error (m) of peak temp co-ord to real fire location	Max error (m) of estimated location to real fire location
0.0	0.0
0.0	0.0
0.0	0.0
0.3	0.0
0.0	0.4
0.0	0.0
0.3	0.0
0.3	0.4
0.0	0.4
0.0	0.0
0.5	0.0
0.0	0.0
0.0	0.4
0.0	0.4
0.0	0.4
0.0	0.4
0.50	**0.35**

Table 1 – 50kw fire location summary

Accepting that the primary role of this system is not initial detection of the fire (there will be much more capable equipment installed to do this), the peak temperature is surpassed at t = 37 s and predicts the position of the fire exactly. Prediction of location by pinpointing the centre of the area above the threshold value returns an accuracy of 0.35 m which is observed to improve with time.

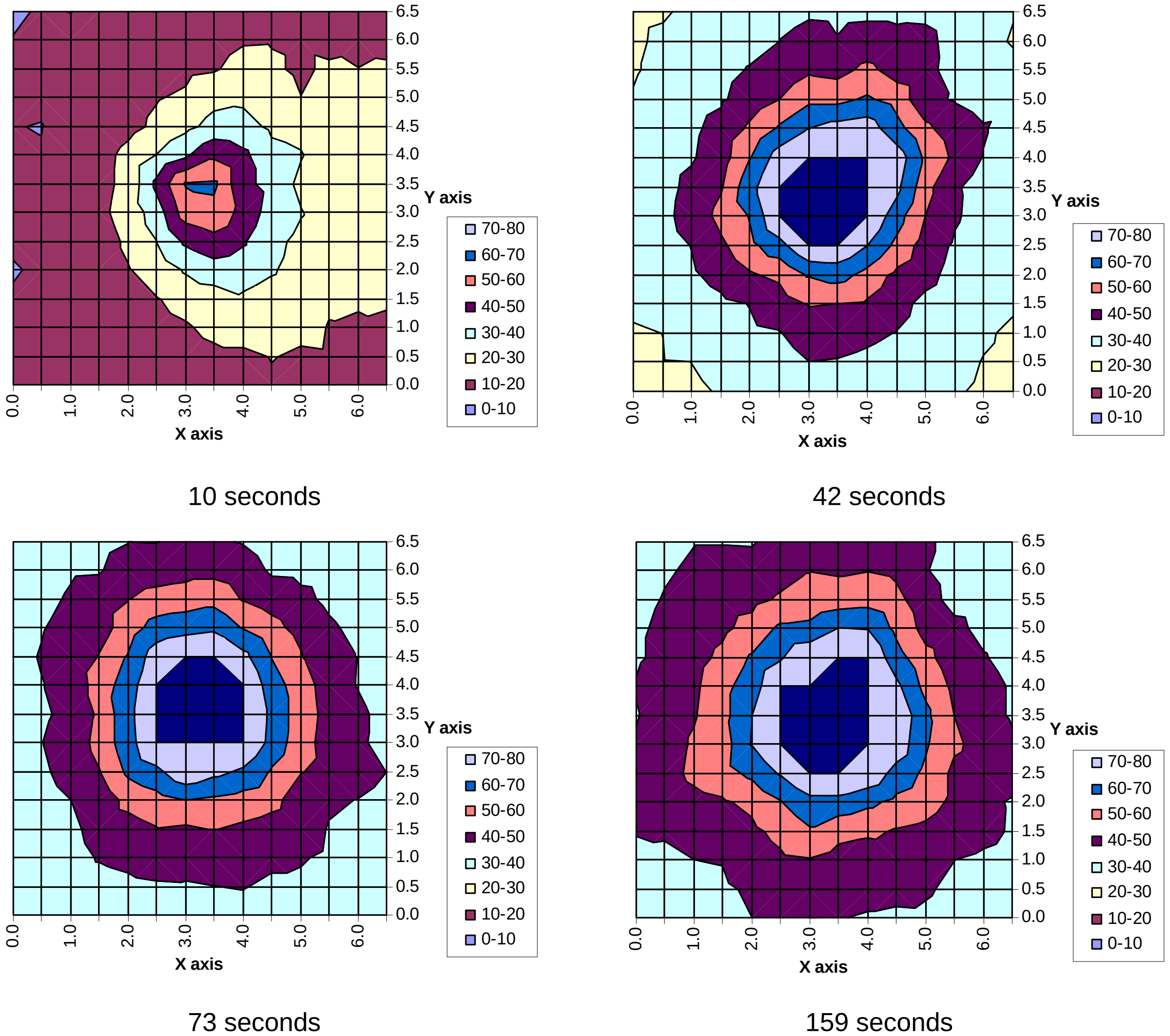


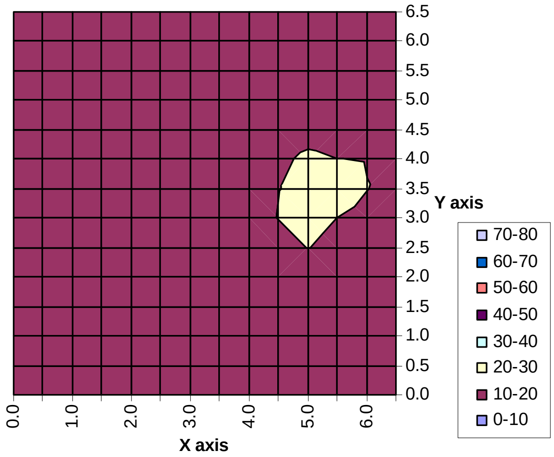
Figure 7 – Temperature maps from a 150 kW fire 3.5 m below the ceiling

Test 26	150kW		(3.25,3.25)			
Time	Peak	Area above	Peak temp location		Estimated fire location	
(sec)	Temp	threshold (m2)	X	Y	X	Y
-10	10.0	0.0	N/A	N/A	N/A	N/A
0	10.0	0.0	N/A	N/A	N/A	N/A
10	61.3	1.0	3.25	3.25	3.25	3.25
21	107.1	6.5	3.25	3.25	3.42	3.42
32	122.5	10.5	3.25	3.25	3.31	3.31
42	120.8	11.5	3.25	3.25	3.42	3.42
53	120.7	12.5	3.25	3.75	3.25	3.25
64	117.3	14.3	3.25	3.75	3.19	3.19
74	122.6	13.8	3.25	3.75	3.27	3.27
85	124.5	14.5	3.25	3.75	3.21	3.21
96	120.6	14.5	3.25	3.25	3.18	3.18
107	120.5	14.8	3.50	3.38	3.17	3.17
117	123.4	14.8	3.50	3.63	3.34	3.34
128	120.9	14.3	3.25	3.75	3.22	3.22
139	122.6	15.0	3.25	3.75	3.18	3.18
149	120.0	15.5	3.38	3.50	3.19	3.19
160	142.4	16.3	3.38	3.50	3.26	3.26
171	128.4	17.0	3.25	3.25	3.22	3.22
182	121.2	15.5	3.25	3.25	3.16	3.16
192	66.7	2.8	3.50	3.25	3.23	3.23

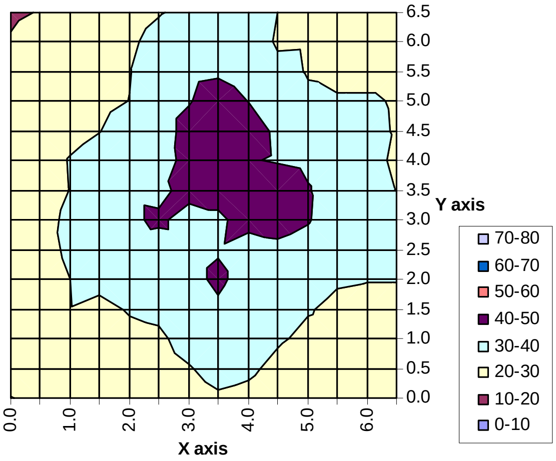
Max error (m) of peak temp co-ord to real fire location	Max error (m) of estimated location to real fire location
0.0	0.0
0.0	0.0
0.0	0.0
0.0	0.2
0.0	0.1
0.0	0.2
0.5	0.0
0.5	0.1
0.5	0.0
0.5	0.1
0.0	0.1
0.3	0.1
0.5	0.1
0.5	0.0
0.5	0.1
0.3	0.1
0.3	0.0
0.0	0.0
0.0	0.1
0.3	0.0
0.50	**0.25**

Table 2 – 150kw fire location summary

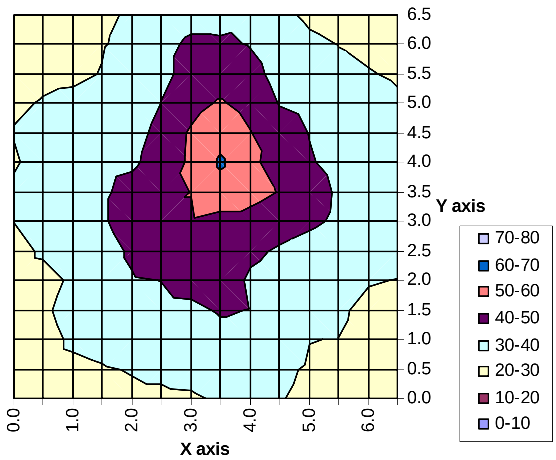
As would be expected with a larger heat output fire the time to detection is reduced to 10 seconds from 37 seconds for the 50 kW fire, and the accuracy of location throughout the entire event is improved. This is attributable to the strengthening of the fire plume (increased buoyancy) with heat release rate making it less susceptible to dispersion and wind effects before reaching the ceiling mounted sensors.



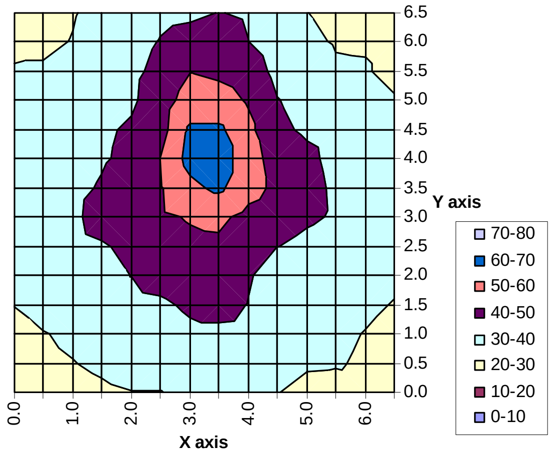
12 seconds



36 seconds



73 seconds



159 seconds

Figure 8 – Temperature maps from a 100 kW fire 3.5 m below the ceiling with significant baffle

Test 18 100kW - 1x1m baffle - @2m (3.25,3.25)

Time (sec)	Peak Temp	Area above threshold (m2)	Peak temp location X	Peak temp location Y	Estimated fire location X	Estimated fire location Y	Max error (m) of peak temp co-ord to real fire location	Max error (m) of estimated location to real fire location
-12	11.0	0.0	N/A	N/A	N/A	N/A	0.0	0.0
0	11.0	0.0	N/A	N/A	N/A	N/A	0.0	0.0
12	21.9	0.0	5.13	3.50	N/A	N/A	1.9	0.0
24	37.5	0.0	4.13	4.00	N/A	N/A	1.2	0.0
36	46.3	0.0	3.88	3.88	N/A	N/A	0.9	0.0
49	53.8	0.8	3.88	3.88	3.83	3.83	0.9	0.8
61	58.6	1.5	3.63	3.88	3.83	3.83	0.7	0.8
73	61.4	2.5	3.63	3.88	3.50	3.50	0.7	0.4
85	61.8	2.3	3.38	4.13	3.33	3.33	0.9	0.1
98	60.6	2.3	3.38	4.00	3.44	3.44	0.8	0.3
110	58.7	2.3	3.13	4.00	3.17	3.17	0.8	0.1
122	64.5	3.3	3.38	4.13	3.62	3.62	0.9	0.5
134	63.2	3.8	3.25	4.25	3.27	3.27	1.0	0.0
146	62.7	3.8	3.38	4.00	3.57	3.57	0.8	0.4
159	66.0	3.3	3.38	4.00	3.42	3.42	0.8	0.2
171	62.2	3.8	3.25	4.25	3.37	3.37	1.0	0.2
183	63.7	3.8	3.38	4.00	3.30	3.30	0.8	0.1
195	50.3	0.3	3.38	3.38	3.50	3.50	0.2	0.4
208	35.8	0.0	3.38	3.38	N/A	N/A	0.2	0.0
220	27.1	0.0	3.25	3.63	N/A	N/A	0.4	0.0
							1.89	**0.82**

Table 3 – 100kw small high level baffled fire

In the confines of a ship's machinery space there may be present much horizontal baffling just below the deckhead such as ventilation ducting and cable trays. This test shows that whilst the location of the peak temperature may be greatly adjusted away from the true position of the fire, location by calculation of the centre point of the area of the ceiling which exceeds the threshold value maintains the accuracy to below 1 metre; well within the accuracy demanded by SIFSS.

The idea of using temperature threshold values for detection and location is appealing since the sensitivity of the system may be simply maintained by adjusting the threshold in accordance with the location of the platform around the world, or / and the current level of activity within the protected space, without increasing the likelihood of false alarms. The performance associated with this methodology improves as the fire increases in size: the speed of detection will be shorter, and accuracy of fire position determination more exact. Deliberately small fires were used in this study to appraise the capability of the system to support the short response times demanded by SIFSS.

Figure 9 and Figure 10 show peak temperatures measured in the 1st minute of a selection of test fires, and the time taken to reach the threshold temperature, respectively.

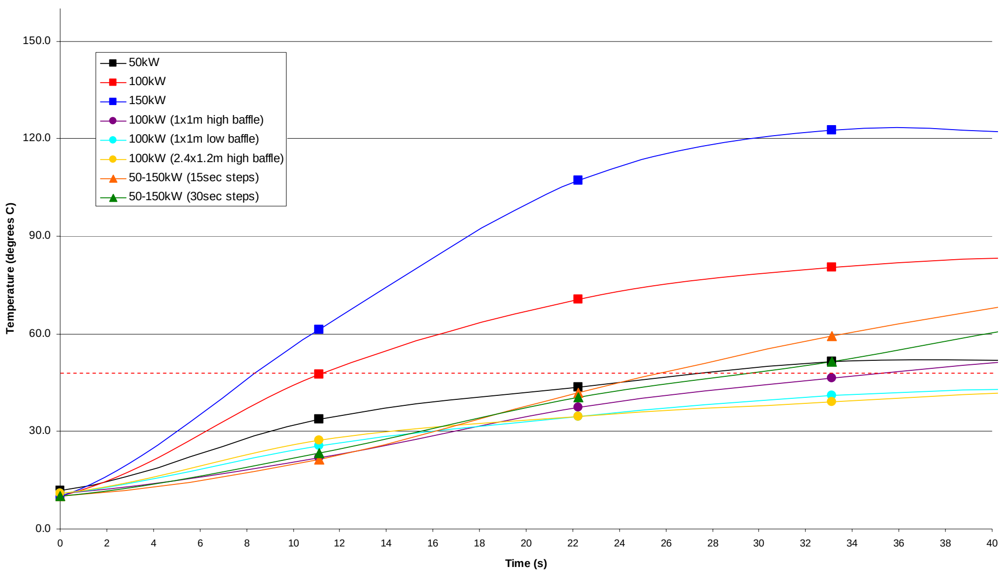


Figure 9 – Peak temperatures measured at the deckhead during the first minute of the fire event

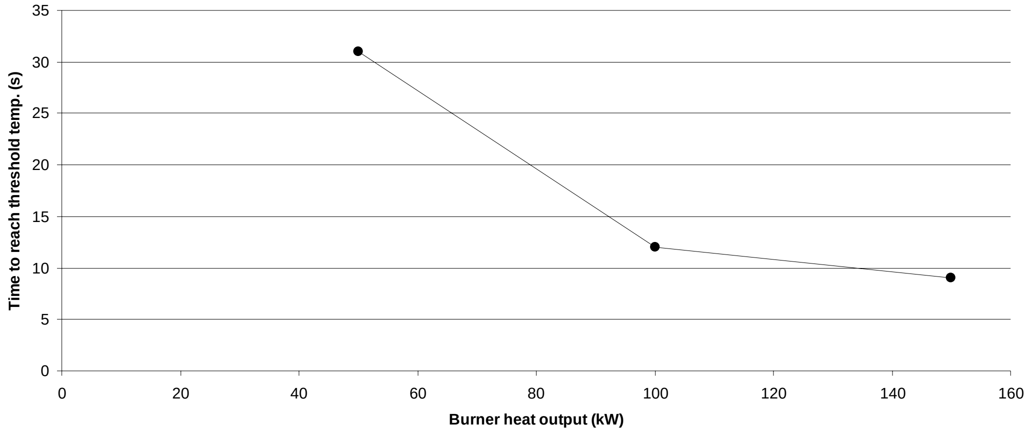


Figure 10 – Time to reach fire detection threshold of 50°C vs. fire size

Figure 11 shows the development of 'over threshold' ceiling areas for fires of 50 kW, 100 kW and 150 kW. Whilst identification of actual heat release rates will be problematic for fires with varying heat output, discernment of relatively small differences (50 kW increments) is good and perhaps integration of appropriate fire zone models into the process could give viable estimations of immediate fire threat levels to underpin SIFSS.

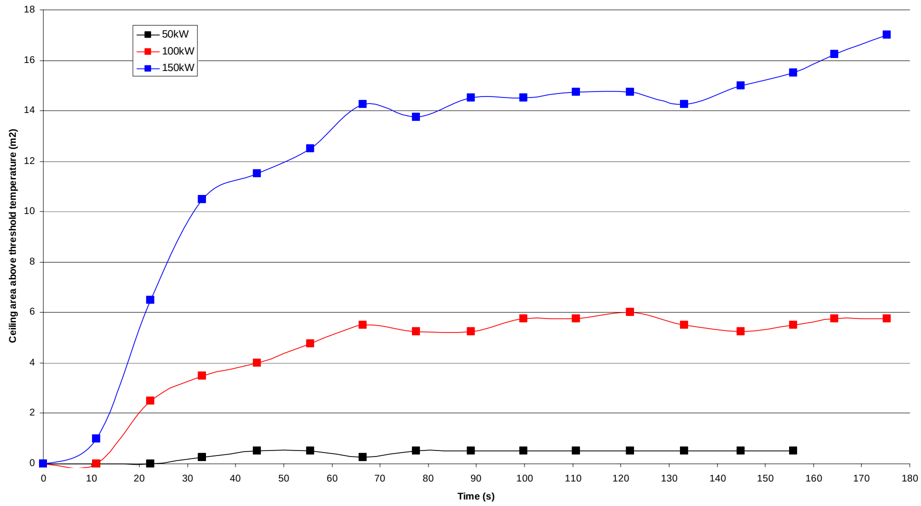


Figure 11 – Ceiling area above threshold of 50°C vs. time

5 Fire location by ‘real’ time image analysis of output from a video flame detection system

There are many visual fire detection systems on the market commonly derived from intruder security application. Of these many concentrate on smoke detection with very few seeking explicitly to recognise flaming. The axonX Signi*Fire* system almost uniquely recognises:

- Intrusion
- Smoke
- Flame
- Offsite flame (flickering off surfaces even when the flame is not directly viewable)

Autonomous location of the seat of fire requires:

- A view of the event simultaneously by 2 or more cameras
- A robust flame recognition algorithm
- The capability to draw a tight box around the flaming event or events
- The capability to transfer the coordinates of the event box to a computer or the platform management system for analysis
- An algorithm to determine the location of the fire within the viewed space from the event box co-ordinates, and the size of the fire from the volume or area or the event box

With the help of the manufacturers of the system the software provided with the Signi*Fire* unit was modified to make the video pixel references of all identified events available on the IP interface for real-time processing such that it may be analysed by the PMS and ultimately guide a robotically directed suppression system to the seat of the fire.

There are a number of ways to determine the position of a common object viewed from multiple observation points. Figure 12 shows the triangulation equations for locating a fire at floor level from 2 parallel cameras. By repeating the calculations in the vertical axis the true three dimensional position may be determined.

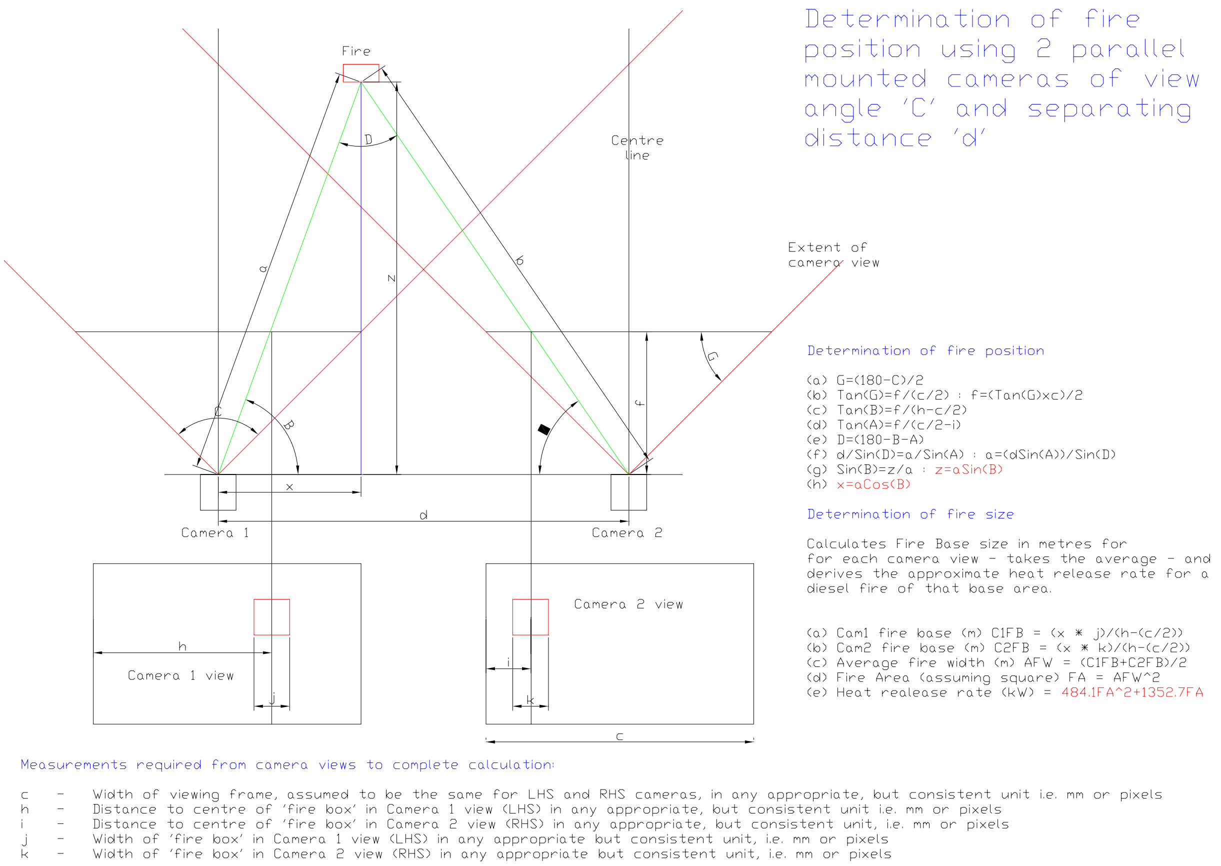


Figure 12 – Determination of fire location and size from analysis of images from 2 parallel cameras

Figure 13 – Experimental configuration showing parallel camera positions

Figure 14 – Low cost B&W cameras used with the Signi-Fire system

Figure 15 and Figure 16 show the left and right camera views of a scenario comprising 2 fires:

Fire 1 (LHS of image): 20m from camera baseline, 2m in from LH camera axis: 100ml Petrol in 0.03m^2 tray
Fire 2 (RHS of image): 15m from camera baseline, 6m in from LH camera axis: 100ml Petrol on 0.03m^2 tray
Fire location information was available 9 seconds after ignition.

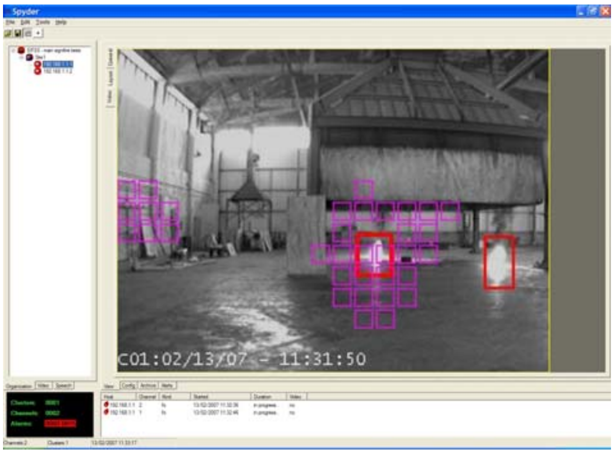


Figure 15 – Left hand camera image

Figure 16 – Right hand camera image

The distinctive red boxes which are automatically generated by the Signi*Fire* system indicate confirmed flaming fire detection whilst the purple boxes indicate areas subject to offsite incident flame flicker.
Using the algorithm described in Figure 12 the location of both fires were calculated as follows:

Fire	Actual Distance from camera baseline (m)	Actual distance from axis of LH camera (m)	Measured distance from camera baseline (m)	Measured distance from axis of LH camera (m)	Measured heat release rate of fire (kW)
1	20	2	19.8	2.1	5.6MW
2	15	6	14.6	6.2	1.4MW

Table 4 – Estimation of fire location and heat release rate by video analysis

Whilst the spatial resolution is very good, estimation of heat release rate is poor due to the over-sizing of the event box around the fires. This is observed to occur for a number of reasons including:

- Sensitivity setting – a lower sensitivity setting draws as tighter box around the event, but this may increase the detection time
- Star burst and blooming effects – against the darkness flames can appear larger than they are due to star burst and blooming effects. Improvements may be possible using filters, irises or higher quality cameras
- Reflections in the immediate vicinity of the fire – Particularly evident in the supplied example the apparent size of the fire is artificially increased due to adjacent reflections on the floor. In this particular instance the floor had become ‘shiny’ from dried foam deposits from another experimental programme and the change in system performance in respect of fire sizing was evident. Again, further tuning of cameras and filters would be expected to improve this.

Overall, increasing background lighting reduced effects that would act to distort fire size estimation. Triangulation algorithms were also developed for tangentially placed cameras, which gave improved common accuracies in all directions. A further algorithm, based on ‘equation of line’ theory was developed for cameras placed at any known angle to each other.

6 Suppression systems in support of SIFSS

If the described systems prove suitable for implementation onboard ship in each of the two scenarios then efforts may turn to exploiting in full the benefit of having precise fire location co-ordinates to underpin the use of novel suppression systems and techniques.

In respect of the ship’s machinery spaces the onus is on limiting the usage of firefighting water especially given the envisaged future move to wholly electric propulsion. For this application technologies such as the IFEX pulsed watermist cannon could be considered or a more conventional high pressure water mist lance system such as FireExpress (see Figure 17 and Figure 18). Whilst the IFEX system is currently offered as a mobile rail-mounted version for tunnel protection the author is not aware of any actual implementations to date. As such, these systems would require mounting on motorised platforms controlled from the PMS.

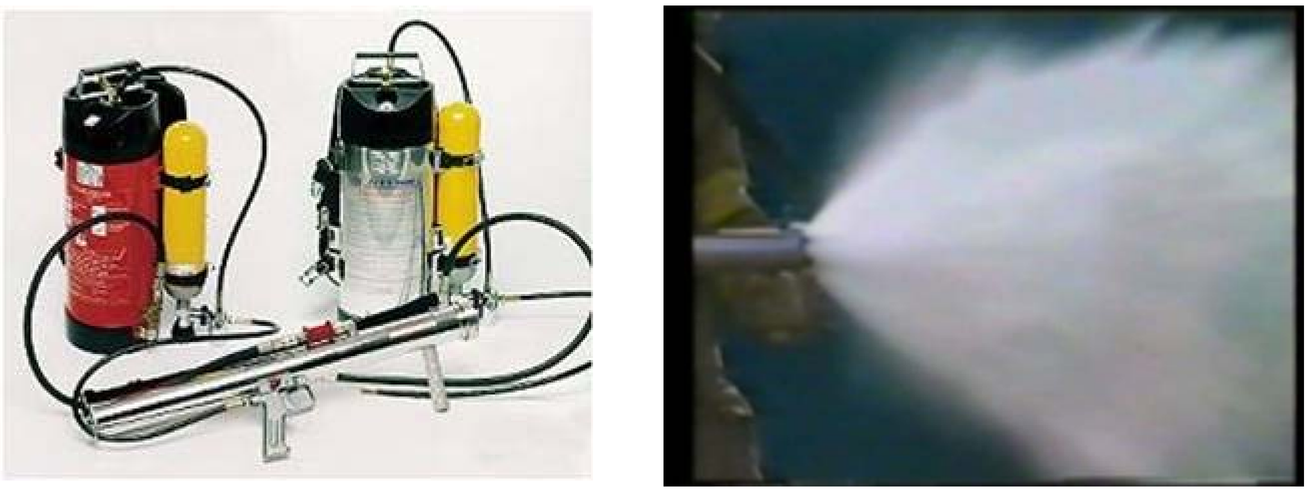


Figure 17 – IFEX

Figure 18 – FireExpress spray lance

The management of fires in vehicle and hangar decks usually requires the application of foam and quite often significant quantities of water and as such the SIFSS action would be to employ robotic versions of established fire-fighting equipment earlier in the fire event than would otherwise be possible with a manual team. Equipment that could be considered might include a robotic branch such as the FireFox offered by Akron Brass, or foam monitors, often used in ‘sweeping’ mode such as those supplied by Ansul, see Figure 19 and Figure 20, respectively.

Figure 19 – FireFox controllable branch

Figure 20 – Ansul Foam Monitor

7 Summary

Advances in effective fire suppression techniques onboard RN platforms, required to react to fleet changes, are impossible without first addressing and improving the current detection systems employed. A major part in this undertaking is the automation of the 1st aid firefighting role usually conducted manually. Inherent in this approach is:

- the capability to automatically locate the seat of the fire
- the capability to automatically appraise the fire size and level of threat
- the capability to automatically apply a response
- an effective suppression system whose operation has low impact on anything other than the fire
- centralised and responsive decision making via the ship’s PMS

The SIFSS research programme, whilst incomplete, has demonstrated that off-the-shelf equipment with limited modification may be used for the location and sizing of fire within compartments comparable to those found onboard ship. By the end of the project end-to-end closed loop response shall be demonstrated controlled by the Rolls-Royce PMS and integrating equipment telemetry, fire precursor sensors, fire detection sensors and a complete set of logic tree responses in addition to the fire location and sizing methodologies described here.

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