FIBER OPTIC CONTROL SYSTEM INTEGRATION

FINAL REPORT

by

G.L. Poppel, W.M. Glasheen, J.C. Russell

General Electric Company
Aircraft Engine Business Group
Advanced Engineering and Technology Programs Department
Cincinnati, Ohio 45215

Prepared for
R.J. Baumbick, Project Manager

National Aeronautics and Space Administration

NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Contract NAS3-24624
A total fiber-optic, integrated propulsion/flight control system concept for advanced fighter aircraft is presented. Fiber optic technology pertaining to this system is identified and evaluated for application readiness. A fiber optic sensor vendor survey was performed, and the results are reported. The advantages of centralized/direct architecture are reviewed, and the concept of the protocol branch is explained. Preliminary protocol branch selections are made based on the F-18/F404 application. Concepts for new optical tools are described. Propulsion system supportability and vulnerability/survivability trade study results show the presented concept is favorable. Development plans for the optical technology and the described system are included.
Trade names or manufacturer's names are used in this report for identification purposes only. This usage does not constitute an official endorsement or disapproval of the products involved, either expressed or implied, by the National Aeronautics and Space Administration, GE, or any subcontractors on the FOCSI program.

In addition, evaluations of named manufacturer's products are judgements based on data supplied by the manufacturer.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.0 SUMMARY</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>2.0 INTRODUCTION</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>3.0 CONTROL SYSTEM SENSOR/ACTUATOR REQUIREMENTS</strong></td>
<td>3</td>
</tr>
<tr>
<td>3.1 F-18 Aircraft</td>
<td>3</td>
</tr>
<tr>
<td>3.1.1 F-18 Flight Control</td>
<td>3</td>
</tr>
<tr>
<td>3.1.2 F404 Propulsion Control</td>
<td>8</td>
</tr>
<tr>
<td>3.2 Generic Aircraft Requirements</td>
<td>11</td>
</tr>
<tr>
<td><strong>4.0 OPTICAL SENSOR VENDOR SURVEY</strong></td>
<td>11</td>
</tr>
<tr>
<td>4.1 Questionnaire and Responses</td>
<td>11</td>
</tr>
<tr>
<td>4.2 Fiber Optic Sensor Evaluations</td>
<td>11</td>
</tr>
<tr>
<td>4.2.1 Performance Requirements</td>
<td>11</td>
</tr>
<tr>
<td>4.2.2 Classification of Fiber Optic Sensors</td>
<td>18</td>
</tr>
<tr>
<td>4.2.3 Development Level</td>
<td></td>
</tr>
<tr>
<td><strong>5.0 FIBER OPTIC COMPONENTS</strong></td>
<td>20</td>
</tr>
<tr>
<td>5.1 Fiber Optic Cable</td>
<td>20</td>
</tr>
<tr>
<td>5.1.1 Single Fiber Versus Fiber Bundle</td>
<td>20</td>
</tr>
<tr>
<td>5.1.2 Multi- and Single-Fiber Cable</td>
<td>23</td>
</tr>
<tr>
<td>5.1.3 Cable To Connector Interface</td>
<td>23</td>
</tr>
<tr>
<td>5.1.4 Qualification-Tested Cables</td>
<td></td>
</tr>
<tr>
<td>5.2 Optical Fibers</td>
<td>23</td>
</tr>
<tr>
<td>5.2.1 Mode Losses</td>
<td>24</td>
</tr>
<tr>
<td>5.2.2 UV Transmission</td>
<td>24</td>
</tr>
<tr>
<td>5.2.3 Single-Mode Fibers</td>
<td></td>
</tr>
<tr>
<td>5.3 Fiber Optic Connectors</td>
<td>24</td>
</tr>
<tr>
<td><strong>5.4 Optical Sources</strong></td>
<td>24</td>
</tr>
<tr>
<td>5.4.1 Reliability</td>
<td>25</td>
</tr>
<tr>
<td>5.4.2 Available Spectra</td>
<td>25</td>
</tr>
<tr>
<td>5.4.3 Optical Power</td>
<td></td>
</tr>
<tr>
<td><strong>5.5 Optical Detectors</strong></td>
<td>25</td>
</tr>
</tbody>
</table>
### TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5.1 Solid State - Avalanche Versus PIN Diodes</td>
<td>25</td>
</tr>
<tr>
<td>5.5.2 Tube Detectors</td>
<td>26</td>
</tr>
<tr>
<td>5.6 Passive Optical Components</td>
<td>26</td>
</tr>
<tr>
<td>5.6.1 Coupler Types</td>
<td>26</td>
</tr>
<tr>
<td>5.6.2 Environmental Limits</td>
<td>27</td>
</tr>
<tr>
<td>5.7 Effectors</td>
<td>27</td>
</tr>
<tr>
<td>5.8 Optical Ignition</td>
<td>27</td>
</tr>
<tr>
<td>6.0 INTEGRATED FIBER OPTIC CONTROL SYSTEM</td>
<td>29</td>
</tr>
<tr>
<td>6.1 Integrated Airframe/Propulsion Control System Architectures (IAPSA) Study</td>
<td>29</td>
</tr>
<tr>
<td>6.2 Centralized/Direct Architecture</td>
<td>30</td>
</tr>
<tr>
<td>6.3 Protocol Branch Method</td>
<td>30</td>
</tr>
<tr>
<td>6.3.1 Preliminary Protocol Branch Selections</td>
<td>32</td>
</tr>
<tr>
<td>6.3.2 Optical Tools For Protocol Branch</td>
<td>35</td>
</tr>
<tr>
<td>6.4 Flight Control System Description</td>
<td>35</td>
</tr>
<tr>
<td>6.5 Propulsion Control System Description</td>
<td>36</td>
</tr>
<tr>
<td>6.5.1 Near Term</td>
<td>36</td>
</tr>
<tr>
<td>6.5.2 Far Term</td>
<td>38</td>
</tr>
<tr>
<td>6.5.3 Off-Engine FADEC Accountability</td>
<td>38</td>
</tr>
<tr>
<td>6.5.4 Pressure Transducer Location</td>
<td>40</td>
</tr>
<tr>
<td>6.5.5 Addressing Off-Engine FADEC Issues</td>
<td>40</td>
</tr>
<tr>
<td>7.0 PROPULSION SYSTEM TRADE STUDIES</td>
<td>42</td>
</tr>
<tr>
<td>7.1 Trade Study Propulsion Systems</td>
<td>42</td>
</tr>
<tr>
<td>7.2 Supportability Study</td>
<td>44</td>
</tr>
<tr>
<td>7.2.1 Approach and Assumptions</td>
<td>44</td>
</tr>
<tr>
<td>7.2.2 Reliability</td>
<td>44</td>
</tr>
<tr>
<td>7.2.3 Maintainability</td>
<td>45</td>
</tr>
<tr>
<td>7.2.4 Life-Cycle Cost (LCC)</td>
<td>46</td>
</tr>
<tr>
<td>7.2.5 Availability</td>
<td>46</td>
</tr>
<tr>
<td>7.3 Survivability/Vulnerability Study</td>
<td>47</td>
</tr>
<tr>
<td>7.3.1 Combat Effectiveness Potential</td>
<td>47</td>
</tr>
<tr>
<td>7.3.2 Susceptibility</td>
<td>47</td>
</tr>
<tr>
<td>7.3.3 Vulnerability</td>
<td>48</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS (Concluded)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0 DEVELOPMENT PLAN</td>
<td></td>
</tr>
<tr>
<td>8.1 Optical Technology</td>
<td>49</td>
</tr>
<tr>
<td>8.2 Optical System</td>
<td>49</td>
</tr>
<tr>
<td>9.0 CONCLUDING REMARKS</td>
<td>54</td>
</tr>
<tr>
<td>APPENDIX A - Fiber Optic Sensor Vendor Questionnaire and Vendors Surveyed</td>
<td>55</td>
</tr>
<tr>
<td>APPENDIX B - Protocol and Sensor Selection</td>
<td>58</td>
</tr>
<tr>
<td>The Protocol Branch Method and Sensor Selection</td>
<td>58</td>
</tr>
<tr>
<td>FOCSI Protocol Branch Selection</td>
<td>59</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>61</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>F-18 Flight Envelope and Bay Area Environment.</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>F-18 Flight Control System Functional Diagram.</td>
<td>5</td>
</tr>
<tr>
<td>3.</td>
<td>F404-400 Engine Control System Interface Diagram.</td>
<td>6</td>
</tr>
<tr>
<td>4.</td>
<td>F404 Electrical System Rollout Breakdown.</td>
<td>7</td>
</tr>
<tr>
<td>5.</td>
<td>Generic Set of Propulsion Control System Sensors and Effectors.</td>
<td>10</td>
</tr>
<tr>
<td>6.</td>
<td>Aircraft Fiber Optic Sensor Requirements.</td>
<td>12</td>
</tr>
<tr>
<td>7.</td>
<td>FOCSI Centralized/Direct Architecture.</td>
<td>31</td>
</tr>
<tr>
<td>8.</td>
<td>Protocol Branch Configuration Example.</td>
<td>33</td>
</tr>
<tr>
<td>9.</td>
<td>Examples of Sensors Using Wavelength Referenced Intensity Protocol.</td>
<td>34</td>
</tr>
<tr>
<td>10.</td>
<td>F404 System Rollout For Near-Term Fiber Optic Aircraft.</td>
<td>37</td>
</tr>
<tr>
<td>11.</td>
<td>F404 System Rollout For Far-Term Fiber Optic Aircraft.</td>
<td>39</td>
</tr>
<tr>
<td>12.</td>
<td>Propulsion Control Systems For Trade Study.</td>
<td>43</td>
</tr>
<tr>
<td>13.</td>
<td>Optical Sensor Development Schedule To Achieve Flight-Quality Hardware.</td>
<td>50</td>
</tr>
<tr>
<td>14.</td>
<td>Optical Component Development Schedule To Achieve Flight-Quality Hardware.</td>
<td>51</td>
</tr>
<tr>
<td>15.</td>
<td>Far-Term Integrated Optical System Milestone Chart.</td>
<td>52</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Aircraft Fiber Optic Sensor Requirements.</td>
<td>8</td>
</tr>
<tr>
<td>2.</td>
<td>Fiber Optic Sensor Evaluations.</td>
<td>13</td>
</tr>
<tr>
<td>3.</td>
<td>Optical Data-Transmission Methods.</td>
<td>19</td>
</tr>
<tr>
<td>4.</td>
<td>Needed Optical Component Development Status.</td>
<td>21</td>
</tr>
<tr>
<td>5.</td>
<td>IAPSA Analytical Results.</td>
<td>29</td>
</tr>
<tr>
<td>6.</td>
<td>Weight/Area Estimate for Trade Study Propulsion Systems.</td>
<td>42</td>
</tr>
<tr>
<td>7.</td>
<td>Propulsion System Supportability Trade Study Results.</td>
<td>45</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A8</td>
<td>Variable Exhaust Nozzle (VEN) Throat Area</td>
</tr>
<tr>
<td>AB</td>
<td>Afterburner</td>
</tr>
<tr>
<td>AOA</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>BH</td>
<td>Compressor Variable Geometry (CVG) Angle</td>
</tr>
<tr>
<td>BL</td>
<td>Fan Variable Geometry (FVG) Angle</td>
</tr>
<tr>
<td>CBP</td>
<td>Compressor Bleed Pressure</td>
</tr>
<tr>
<td>CVG</td>
<td>Compressor Variable Geometry</td>
</tr>
<tr>
<td>ECU</td>
<td>Electrical Control Unit</td>
</tr>
<tr>
<td>EME</td>
<td>Electromagnetic Effects</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>EMP</td>
<td>Electromagnetic Pulse</td>
</tr>
<tr>
<td>FADEC</td>
<td>Full-Authority Digital Electronic Control</td>
</tr>
<tr>
<td>F/B</td>
<td>Feedback</td>
</tr>
<tr>
<td>FVG</td>
<td>Fan Variable Geometry</td>
</tr>
<tr>
<td>LED</td>
<td>Light-Emitting Diode</td>
</tr>
<tr>
<td>LRU</td>
<td>Line-Replaceable Unit</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transformer</td>
</tr>
<tr>
<td>NH</td>
<td>Compressor/High Pressure Turbine Speed</td>
</tr>
<tr>
<td>NL</td>
<td>Fan/Low Pressure Turbine Speed</td>
</tr>
<tr>
<td>P0</td>
<td>Ambient Air Pressure</td>
</tr>
<tr>
<td>P1</td>
<td>Engine Inlet Pressure</td>
</tr>
<tr>
<td>P5</td>
<td>Turbine Discharge Pressure</td>
</tr>
<tr>
<td>PLA</td>
<td>Power Lever Angle</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Lever Control</td>
</tr>
<tr>
<td>PS3</td>
<td>Compressor Discharge Static Pressure</td>
</tr>
<tr>
<td>RVDT</td>
<td>Rotary Variable Differential Transformer</td>
</tr>
<tr>
<td>T1</td>
<td>Engine Inlet Temperature</td>
</tr>
<tr>
<td>T25</td>
<td>Compressor Inlet Temperature</td>
</tr>
<tr>
<td>T3</td>
<td>Compressor Discharge Temperature</td>
</tr>
<tr>
<td>T4</td>
<td>Turbine Inlet Temperature</td>
</tr>
<tr>
<td>T5</td>
<td>Low Pressure Turbine Discharge Temperature</td>
</tr>
<tr>
<td>T/C</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>TM</td>
<td>Torque Motor</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VABIA</td>
<td>Variable-Area Bypass Injector Aft</td>
</tr>
<tr>
<td>VABIF</td>
<td>Variable-Area Bypass Injector Forward</td>
</tr>
<tr>
<td>VEN</td>
<td>Variable Exhaust Nozzle</td>
</tr>
<tr>
<td>VG</td>
<td>Variable Geometry</td>
</tr>
<tr>
<td>WF</td>
<td>Main Fuel Flow</td>
</tr>
<tr>
<td>WR</td>
<td>Afterburner Fuel Flow</td>
</tr>
<tr>
<td>WRM</td>
<td>Afterburner Main Fuel Flow</td>
</tr>
<tr>
<td>WRP</td>
<td>Afterburner Pilot Fuel Flow</td>
</tr>
</tbody>
</table>
1.0 SUMMARY

The program objectives were to define a total fiber-optic, integrated propulsion/flight control system, to determine the state of the technology of fiber optic sensors and components for use in integrated control systems, and to propose a schedule for bringing this technology to the point where it can be incorporated into future advanced fighter aircraft systems. The program effort comprised the following tasks:

I. Fiber Optic Sensor/Actuator Requirements - Control system sensor and actuator types, requirements, and environments were identified based on an advanced fighter aircraft application. The F-18/F404 application was used as an example.

II. Optical Sensor Vendor Survey - A vendor survey was conducted to assess the status of fiber optic sensor technology, available types, and level of development.

III. Fiber Optic Components - Requirements and recommendations were studied for components, such as effectors, waveguides, connectors, light sources, and detectors, needed to configure aircraft control system optical circuits.

IV. Integrated Fiber Optic System - A total fiber-optic, integrated propulsion/flight control system for an advanced fighter aircraft was conceptualized. The advantages of centralized/direct architecture were reviewed, and the concept of the protocol branch was explained. Preliminary protocol branch sensors were selected. Off-engine propulsion control issues were addressed.

V. Propulsion System Trade Studies - Supportability and vulnerability trade studies were performed to evaluate fiber optic propulsion systems relative to a baseline electrical system.

VI. Development Plan - Schedules and cost estimates to ready optical technology for advanced aircraft implementation and a milestone chart for development of the fiber optic control system through a demonstrational flight test were provided.

The benefits of relocating all aircraft electronics in a centralized bay are realized by efficiently connecting system components using optical protocol methods. Numerous optical sensors and components need development to meet aircraft requirements.
The Fiber Optic Control System Integration program contemplated by NASA Lewis and the Tri-Services fulfills an increasing need to provide immunity to electromagnetic effects (EME) for the controls and other avionic systems of advanced military aircraft of the 1990's.

Besides providing immunity to electromagnetic effects, namely electromagnetic interference (EMI), electromagnetic pulse (EMP), nuclear radiation, and lightning, use of optical components (especially fiber optic cables for data/command transmission) is expected to reduce the weight and complexity of control systems.

Several Government and industry-funded programs are underway to develop architectures, control modes, and hardware for integrated controls, as well as fiber optic waveguides and optical devices. However, a comprehensive effort is needed to assess the optical technology readiness for making "fly by light" demonstration a reality.
3.0 CONTROL SYSTEM SENSOR/ACTUATOR REQUIREMENTS

3.1 F-18 AIRCRAFT

The F-18 application serves as an example of the kinds and numbers of control system sensors and actuators in use on a modern fighter aircraft and the environment they must operate in. In Sections 6.4 and 6.5, this control system will also serve as a model for configuring an all-optical version. Figure 1 shows an outline of the F-18 aircraft, an F-18 flight envelope, and a description of the environment in three areas where electronic units are located. Temperatures given for the engine area are for once-per-flight extreme transients.

3.1.1 F-18 Flight Control

A functional diagram of the existing F-18 flight control system is shown in Figure 2. It includes the following actuator set and sensor set:

<table>
<thead>
<tr>
<th><strong>Actuator Set</strong></th>
<th><strong>Sensor Set</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator, trim, longitudinal feel</td>
<td>Accelerometers, linear</td>
</tr>
<tr>
<td>Actuator, ratio changer</td>
<td>Gyroscope, rate (3 axes)</td>
</tr>
<tr>
<td>Cylinder, speed brake</td>
<td>Position, linear, control stick</td>
</tr>
<tr>
<td>Drive unit, wing fold</td>
<td>Position, linear, rudder pedals</td>
</tr>
<tr>
<td>Release, ram air door</td>
<td>Position, linear, servocylinders</td>
</tr>
<tr>
<td>Servocylinder, aileron</td>
<td>Pressure sensor, air data (AOA)</td>
</tr>
<tr>
<td>Servocylinder, rudder</td>
<td>Switch, FCS control panel</td>
</tr>
<tr>
<td>Servocylinder, stabilator</td>
<td>Switch, speed brake proximity</td>
</tr>
<tr>
<td>Servocylinder, leading-edge flap</td>
<td>Switch, wing fold inhibit</td>
</tr>
<tr>
<td>Servocylinder, trailing-edge flap</td>
<td>Switch, wing lock warning</td>
</tr>
</tbody>
</table>

3.1.2 F404 Propulsion Control

The complexity of the existing F404 propulsion control system is shown by the engine control system interface diagram in Figure 3. Figure 4 is a scaled rollout sketch of the engine electrical system showing the location and number of individual sensors, components, and interconnection routings. This sketch is also useful in comparing electrical versus optical cable weights, as reported in Section 7.1. The following are present:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 Pressure Sensors</td>
<td>5 Torque Motors</td>
</tr>
<tr>
<td></td>
<td>3 Shaft Speed Sensors</td>
<td>5 Solenoids</td>
</tr>
<tr>
<td></td>
<td>9 Temperature Sensors</td>
<td>1 Rotary Position Sensor</td>
</tr>
<tr>
<td></td>
<td>1 Flow Sensor</td>
<td>5 Linear Position Sensors</td>
</tr>
<tr>
<td></td>
<td>1 Liquid Level Sensor</td>
<td>1 Flame Detector</td>
</tr>
<tr>
<td></td>
<td>5 Switches</td>
<td>1 Linear Accelerometer</td>
</tr>
</tbody>
</table>
Figure 1. F-18 Flight Envelope and Bay Area Environment.
Figure 3. F404-400 Engine Control System Interface Diagram.
Figure 4. F404 Electrical System Rollout Breakdown.
3.2 GENERIC AIRCRAFT REQUIREMENTS

The F-18 propulsion/flight control system sensors are a specific subset of sensors which may be selected for future control system designs. Having a variety of sensors available for selection provides flexibility and optimization of the control system. The optical sensor Vendor survey (Section 4.0) thus required the identification of a full set of engine/airframe sensors, including a description of the characteristics and operating environments.

Figure 5 depicts a generic set of propulsion system effectors and sensors and the approximate positions along the engine axis. Table 1 identifies the performance requirements of range, accuracy, time response, and environment for a full set of generic aircraft sensors. The rotary shaft speed sensor and pyrometer require small response times in order to follow high-speed rotating discontinuities.

<table>
<thead>
<tr>
<th>Parameter (Redundancy)</th>
<th>Range</th>
<th>Accuracy</th>
<th>Response</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperatures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Two Each)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T&lt;sub&gt;1&lt;/sub&gt;</td>
<td>-54° to 230° C</td>
<td>±0.21% Pt</td>
<td>4.3 s</td>
<td>200° C +</td>
</tr>
<tr>
<td>T&lt;sub&gt;25&lt;/sub&gt;</td>
<td>-54° to 260° C</td>
<td>±0.21% Pt</td>
<td>at</td>
<td>200° C at</td>
</tr>
<tr>
<td>T&lt;sub&gt;3&lt;/sub&gt;</td>
<td>260° to 650° C</td>
<td>±0.22% Pt</td>
<td>50 kg/m²</td>
<td>315° C Connector</td>
</tr>
<tr>
<td>T&lt;sub&gt;4&lt;/sub&gt;</td>
<td>260° to 1650° C</td>
<td>±0.22% Pt</td>
<td>per</td>
<td>540° C Interface</td>
</tr>
<tr>
<td>T&lt;sub&gt;5&lt;/sub&gt;</td>
<td>260° to 1095° C</td>
<td>±0.22% Pt</td>
<td>second</td>
<td>425° C +</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-54° C to max of range at probe</td>
</tr>
<tr>
<td>Pressures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Two Each)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔP/P</td>
<td>0-117 ΔkPa</td>
<td>±0.2%</td>
<td>10 ms</td>
<td>-54° to 120° C</td>
</tr>
<tr>
<td>(Two Each)</td>
<td></td>
<td></td>
<td></td>
<td>(Cooled)</td>
</tr>
<tr>
<td>ΔG/P</td>
<td>1035 kPa line</td>
<td>Full</td>
<td></td>
<td>-54° to 200° C</td>
</tr>
<tr>
<td>(Two Each)</td>
<td></td>
<td></td>
<td></td>
<td>(Uncooled)</td>
</tr>
<tr>
<td>ΔCBP</td>
<td>0-690 ΔkPaA</td>
<td>Scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔCBP</td>
<td>3445 kPa line</td>
<td>Scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>0-140 kPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lube</td>
<td>0-345 kPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;5&lt;/sub&gt;</td>
<td>0-415 kPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ps3&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0-3445 kPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Four Each)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;9&lt;/sub&gt;</td>
<td>0-110 kPa</td>
<td>±0.04% Full</td>
<td>10 ms</td>
<td>-54° to 190° C</td>
</tr>
<tr>
<td>P&lt;sub&gt;10&lt;/sub&gt;</td>
<td>0-220 kPa</td>
<td>Scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lube Level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mil-L-7808 Oil)</td>
<td>0 to 0.015 m³</td>
<td>±2% Full</td>
<td>1 s</td>
<td>690 kPa,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scale</td>
<td></td>
<td>-54° to 150° C</td>
</tr>
<tr>
<td>Fuel Flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Two Each)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WF</td>
<td>135-9,075 kg/hr (1-70 gpm)</td>
<td>±1.5%</td>
<td>2 ms</td>
<td>-54° to 150° C, 85 bar (Fuel)</td>
</tr>
<tr>
<td>WR</td>
<td>270-18,145 kg/hr (2-135 gpm)</td>
<td>Full</td>
<td>Scale</td>
<td>-54° to 200° C (Air)</td>
</tr>
<tr>
<td>WR</td>
<td>455-27,215 kg/hr (3-200 gpm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1. Aircraft Fiber Optic Sensor Requirements (Concluded).

<table>
<thead>
<tr>
<th>Parameter (Redundancy)</th>
<th>Range</th>
<th>Accuracy</th>
<th>Time Response</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Position (Two Each)</td>
<td>WF 1.25 - 20 cm Stroke</td>
<td>±1.5% Full Scale</td>
<td>2 ms</td>
<td>-54° to 175° C, 205-550 bar Fluid Internal to Actuator; Up to 200° C at Connector</td>
</tr>
<tr>
<td>Flight Surfaces (4) (1 or 2)</td>
<td>4 cm Stroke 15 cm Stroke 30 cm Stroke</td>
<td>±1% Full Scale</td>
<td>2 ms</td>
<td>-54° to 315° C</td>
</tr>
<tr>
<td>PLA (2)</td>
<td>0-120°</td>
<td>±1% F.S.</td>
<td>2 ms</td>
<td>-54° to 190° C</td>
</tr>
<tr>
<td>Linear Acceleration (8)</td>
<td>± 40m/s²</td>
<td>±0.5% F.S.</td>
<td>2 ms</td>
<td>-54° to 190° C</td>
</tr>
<tr>
<td>Shaft rpm (2) (Response is related to toothed-wheel Frequency)</td>
<td>1,500-15,000</td>
<td>±0.1% F.S.</td>
<td>30 µs</td>
<td>-54° to 315° C at Body; Up to 200° C at Connector</td>
</tr>
<tr>
<td>Angular Rate (8)</td>
<td>±3.5 rad/s</td>
<td>±0.5% F.S.</td>
<td>2 ms</td>
<td>-54° to 190° C</td>
</tr>
<tr>
<td>Vibration (1)</td>
<td>0-50 &quot;G's&quot; Peak</td>
<td>±5% Reading Inherent Resonance &gt; 3 kHz, Flat Within 5% for 25 to 300 Hz</td>
<td>2 ms</td>
<td>-54° to 370° C, 500 &quot;G's&quot; Peak</td>
</tr>
<tr>
<td>Impending Filter Bypass Switch (1)</td>
<td>70-415 ΔkPa 690-8275 kPa Line (Fluids: Fuel, Hydraulic, Lube)</td>
<td>±5% F.S.</td>
<td>1 s</td>
<td>-54° to 150° C</td>
</tr>
<tr>
<td>Pyrometer (2)</td>
<td>540°-1095° C (Target) 845°-980° C (Response is related to turbine blade-passing frequency)</td>
<td>±10° C 10 µs</td>
<td>260° to 1095° C at Tip -54° to 540° C at Connector</td>
<td></td>
</tr>
<tr>
<td>Tip Clearance (1)</td>
<td>Up to 0.3 cm</td>
<td>± 50 µm</td>
<td>4 ms</td>
<td>As Pyrometer</td>
</tr>
<tr>
<td>Lube Debris (1)</td>
<td>0.5 to 1.0 mm</td>
<td>95%</td>
<td>2 ms</td>
<td>-54° to 150° C</td>
</tr>
<tr>
<td>Flame Sensor (1) (Range: per commercially pure propane flame)</td>
<td>&lt; 290 nm</td>
<td>Indication</td>
<td>2 ms</td>
<td>-54° to 370° C</td>
</tr>
</tbody>
</table>
Figure 5. Generic Set of Propulsion Control System Sensors and Effectors.
4.0 OPTICAL SENSOR VENDOR SURVEY

The purpose of the fiber optic sensor vendor survey was to evaluate the status of fiber optic sensor technology in industry and to aid in providing a schedule and cost estimate to ready that technology for aircraft system bench testing. The survey was performed from April through September 1986.

4.1 QUESTIONNAIRE AND RESPONSES

A total of 78 vendors were surveyed. Appendix A presents a list of the vendors surveyed and a copy of the survey questionnaire form. The survey consisted of a letter explaining the purpose of the survey, the questionnaire form, and a copy of the sensor requirements as shown in Table 1.

The vendors responded in many ways. Of those actively working on fiber optic sensors, some filled out the questionnaire, some only sent literature, others only described their work over the telephone. A total of 26 vendors indicated one or more fiber optic sensors at some stage of development. A matrix of vendor versus sensor type is shown in Figure 6.

4.2 FIBER OPTIC SENSOR EVALUATIONS

Vendor survey data were used to compile evaluation charts (Table 2). Where information such as transduction technique was not available, the column is blank. Where the sensor is based on optical pyrometry, the transduction technique is described as collection. The rating methods are described below.

4.2.1 Performance Requirements

A fiber optic sensor must meet control system design needs and survive in the aircraft/engine environment. The sensor survey responses were rated in the categories of range, accuracy, environment, and response with respect to the requirement charts in Table 1 in the following manner:

3 - Meets requirements
2 - Close to meeting requirements
1 - Far short of meeting requirements or capability not determined

The performance categories are mutually exclusive. The sensor may meet the accuracy requirement but not the environment because room temperature accuracy is reported. In most cases, thermal effect on accuracy is not established.

4.2.2 Classification of Fiber Optic Sensors

Fiber optic sensors have two distinct attributes: transduction technique and transmission protocol.
Table 2. Fiber Optic Sensor Evaluations.

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Basco and Wilcox</th>
<th>Focal Marine</th>
<th>MTI Instruments</th>
<th>Consolidated Controls</th>
<th>Azar</th>
<th>EO Tech</th>
<th>Teleeye Ryan</th>
<th>Televue Ryan</th>
<th>Context</th>
<th>Pessey</th>
<th>Noll/Carbon Dodge</th>
<th>Planar</th>
<th>Optelecom</th>
<th>Starmate</th>
<th>Technology Dynamics</th>
<th>OPTECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>All C.D.E, D.E</td>
<td>All C</td>
<td>E</td>
<td>C</td>
<td>E</td>
<td>C.D.E</td>
<td>'B'</td>
<td>F</td>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>C.D.E</td>
<td>All</td>
<td>C.D.E</td>
<td>All</td>
</tr>
<tr>
<td>Accuracy</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Environment</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Response</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Light Source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LED</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>White</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>Intensity</td>
<td>Intensity</td>
<td>Intensity</td>
<td>Intensity</td>
<td>Intensity</td>
<td>Intensity</td>
<td>Time division multiples</td>
<td>Intensity × ratio</td>
<td>Wavelength coded</td>
<td>Interferometric</td>
<td>Time division multiples</td>
<td>A shift</td>
<td>A shift</td>
<td>Intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transduction</td>
<td>Micro-bend</td>
<td>Micro-bend</td>
<td>Reflection</td>
<td>Reflection</td>
<td>Reflection</td>
<td>Reflection</td>
<td>Micro-bend</td>
<td>Bourdon tube</td>
<td>Diffraction</td>
<td>Reflection</td>
<td>Reflection</td>
<td>Reflection</td>
<td>Reflection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technique</td>
<td>Development Level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Range Code:  
(A) 0-117 kPa, 1035 kPa  
(B) 0-690 kPa, 3445 kPa  
(C) 0-140 kPa  
(D) 0-415 kPa  
(E) 0-3445 kPa  
R.T. Room Temperature
<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Range</th>
<th>Accuracy</th>
<th>Environment</th>
<th>Response</th>
<th>Light Source</th>
<th>White</th>
<th>Pyrometer</th>
<th>Laser</th>
<th>Transmission Protocol</th>
<th>Collection</th>
<th>Transduction Technique</th>
<th>Development Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosamunt</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
|                    | 3     | 3        | 1           | 3        | 1            |       |           |�

Table 2. Fiber Optic Sensor Evaluations (Continued).
Table 2. Fiber Optic Sensor Evaluations (Continued).

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Babcock and Wilcox</th>
<th>Astar</th>
<th>Astar and Acceber</th>
<th>Summorns Precision</th>
<th>GE AEBG</th>
<th>EOTec</th>
<th>Conax</th>
<th>Conax</th>
<th>TeleEye</th>
<th>Pyran</th>
<th>Liurn</th>
<th>McDonnell Douglas</th>
<th>Fujhure</th>
<th>Technology Dynamics</th>
<th>Conax</th>
<th>Consolidated Controls</th>
<th>Pelgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>C</td>
<td>A</td>
<td>D</td>
<td>A</td>
<td>D</td>
<td>A</td>
<td>D</td>
<td>A</td>
<td>C</td>
<td>1</td>
<td>B</td>
<td>A</td>
<td>3</td>
<td>3</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrometer</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Transmission      | Intensity 
A ratio | Intensity 
ratio | Intensity 
A ratio | Intensity A ratio | Intensity A ratio | Intensity A ratio | Intensity A ratio | Pulse delay | Interferometric | Spectral shift | Intensity A ratio | Intensity wavelength coded |
| Protocol          |                   |       |                   |                   |        |       |       |       |         |       |       |                   |        |                   |       |
| Transduction      | Collection        | Reflection | Collection | Reflection from bimetal | Collection | Collection | Collection | Fluorescence decay | Raman effect | Reflection | |
| Technique         |                   |         |                   |                   |        |       |       |       |         |       |       |                   |        |                   |       |
| Development Level | 3                 | 3     | 3                 | 1                 | 3      | 2     | 2     | 3     | 4       | 2     | 2     | 3                 | 2      |                   |       |

Range Code: (A) -54° to 280°C
(B) 260° to 650°C
(C) 260° to 1095°C
(D) 260° to 1650°C
Table 2. Fiber Optic Sensor Evaluations (Continued).

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Linear Position</th>
<th>Angular Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Functions</td>
<td>Contra.</td>
</tr>
<tr>
<td>Range</td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td>Accuracy</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Environment</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Response</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Light Source</td>
<td>LED</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>White</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Pyrometer</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Laser</td>
<td>✓</td>
</tr>
<tr>
<td>Transmission Protocol</td>
<td>Fiber array</td>
<td>Intensity Ratio</td>
</tr>
<tr>
<td>Development Level</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Environment Code: (A) to 200°C
(B) to 315°C
R T Room Temperature
Table 2. Fiber Optic Sensor Evaluations (Concluded).

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Angular Velocity</th>
<th>Shaft Speed</th>
<th>Mass Flow</th>
<th>Blade Tip Clearance</th>
<th>Liquid Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Focal Marine</td>
<td>No Contact</td>
<td>Distance</td>
<td>GE AID</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Accuracy</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Environment</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Response</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Light Source</td>
<td>LED</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>White</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Pyrometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laser</td>
<td></td>
<td></td>
<td>Microbend Pressure</td>
<td>Reflective</td>
</tr>
<tr>
<td></td>
<td>Transmission</td>
<td>Pulse</td>
<td>Interfero-</td>
<td>Pulse</td>
<td>Reflective</td>
</tr>
<tr>
<td></td>
<td>Protocol</td>
<td>rate</td>
<td>metric</td>
<td>rate</td>
<td>Reflection</td>
</tr>
<tr>
<td></td>
<td>Transduction</td>
<td>Reflection</td>
<td>Magneto</td>
<td>Reflection</td>
<td>Reflection</td>
</tr>
<tr>
<td></td>
<td>Technique</td>
<td>Vortex</td>
<td>Shedding</td>
<td>Pressure</td>
<td>Reflection</td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>


All sensors employing a deflecting diaphragm as the sensing element use one transduction technique, as do all sensors that use the stress-related photoelastic effect to affect the state of polarization. Generally, sensors that are extrinsic and have mechanically moving parts are more complex than those which are intrinsic and rely solely on a bulk material property.

The sensor data-transmission method, or protocol, will generally fall within one of 12 categories shown in Table 3. In many cases, a transduction technique allows the choice of several protocols. Protocol choices relate to the ability to multiplex several sensor signals together, thus affecting control system complexity and weight. Protocol is of key importance to the integrated fiber optic control system concept presented in Section 6.0.

### 4.2.3 Development Level

The development level indicates the remaining time and cost projected before the sensor is ready for aircraft use and the confidence level that the technical problems are solvable. Six levels of rating were used because of the wide variety of responses from the survey. It is assumed for all levels that any electronics accompanying the sensor must be redesigned for aircraft use. The levels are as follows:

- **Level 6** - Ready for use in an aircraft system.
- **Level 5** - Prototypes available in an aircraft design. Hardware is developed and has been substantially tested. Ready for users to try out.
- **Level 4** - Prototypes available in a nonaircraft design. Otherwise same as Level 5. The concept may not necessarily work in an aircraft environment.
- **Level 3** - Development phase. The concept is proven, and hardware is being made for in-house testing.
- **Level 2** - Research phase. Determining the viability of the concept.
- **Level 1** - Intention phase. Have concept in mind but work has not started.

The general absence of Levels 5 or 6 indicates general low development effort in fiber optic sensors for aircraft application.
Table 3. Optical Data-Transmission Methods.

1. Intensity Variation - Absolute returned intensity. As with microbend sensors, this is strictly the low-frequency amplitude variation of one or more wavelengths.

2. Modulated Intensity - Intensity at one carrier frequency. This is a method of shifting the low-frequency domain data into a higher frequency space. The light source is subject to constant frequency pulsing. This technique allows multiple sensor returns on one fiber by selecting the various carriers with narrow electronic band-passing, possibly at a particular wavelength.

3. Intensity Difference - Variation in amplitude of one wavelength compared to a reference wavelength within the same fiber. The two wavelengths should be close enough to allow proper correction but not so similar as to inhibit good separation.

4. Wavelength Shift - Absolute wavelength variation, as produced by rotating a grating supplied with white light for instance.

5. Modulated Wavelength - Frequency modulation. The higher frequency space equivalent of 4.

6. Pulse Rate - Period between returned pulses. Variation in frequency of a pulse train. As in speed sensors, interferometric rate sensors, Doppler devices, etc.

7. Digital Pulse Encoding - A string of pulses representing a digital value, or word. Data could be coded in binary or Gray code or represented by the number of pulses in a group.

8. Pulse Delay - Variation in pulse return time due to variation in the optical path length or velocity in the medium.

9. Pulse Duration - Pulse decay time. The variation of a pulse length as in temperature-dependent persistence of an ultraviolet-excited fluorescence.

10. Image Transmission - Transmission of position information as complete as a visual image of good resolution or as compact as the position of a shutter to three or four fiber positions.

11. Polarization Rotation - Variation in the relative magnitudes of the fast and slow modes of propagation within a polarization preserving single-mode fiber. The photoelastic effect will produce this rotation.

12. Digital Wavelength Coding - The presence of wavelength x asserts a bit within a parallel data word composed of n wavelength possibilities. Digital bits have distinct wavelengths.
5.0 FIBER OPTIC COMPONENTS

The fiber optic components needed to configure aircraft control system optical circuits include fiber cable, connectors, sources, detectors, and couplers. Effectors for actuation control and engine main and afterburner igniters are also needed. This section describes the aircraft application requirements and near-term usage recommendations for these components based on current capabilities. The information is summarized in Table 4.

5.1 FIBER OPTIC CABLE

Requirements include resistance to a wide temperature range, resistance to radiation, temperature cycling, aging, high-level vibration (50 "g's" on an engine), contamination, and handling abuse.

5.1.1 Single Fiber Versus Fiber Bundle

The majority of fiber optic lines carry data or pulses, and single-fiber paths are appropriate for these applications. Dual or even triple lines can be used for reliability, but they should be separated within the cables and connectors. Data from each can be merged at the sensor and/or detector electronics.

Fiber optic bundles are more susceptible to vibration damage and are more complicated to manufacture than single-fiber cables. Nevertheless, when raw optical energy is being transmitted, such as in the flame sensor, fiber optic bundles with a large overall diameter (≈ 3 mm) allow more throughput.

5.1.2 Multi- and Single-Fiber Cable

The generic form expected for aircraft applications of a multifiber design consists of each fiber or fiber bundle, loosely buffered inside a sleeve, surrounded by a relatively soft layer for damping, and housed inside a solid tube for sealing and stiffness. A final outside layer provides abrasion resistance. For short harness assemblies, bundling single-fiber cables and splitting them off into separate cables is also possible, unless weight and bundle diameter become prohibitive.

A loose buffer tube prevents vibration energy and dimensional changes caused by temperature from being transmitted directly to the fiber. The fiber needs to be longer than the exterior cable parts to decrease tension over the temperature range. Since the buffer has a higher thermal coefficient of expansion than glass, a change in length forces the fiber into a helix shape, with losses associated with microbending and compressive forces.

A layer of loose fibrous material between the buffer tube arrangement and the outside protective layers would help absorb vibration, impact, and
<table>
<thead>
<tr>
<th>Fiber</th>
<th>Communication style-multimode (0.8 to 1.6 μm)</th>
<th>Ready for use</th>
<th>Needs development</th>
<th>Not available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 200°C: All applications except those given below</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Up to 370°C: Aircraft position sensors, engine mid-range temperature and vibration sensors</td>
<td>Metal coated</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All dielectric</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>Up to 540°C: Engine upper range temperature sensors, turbine tip clearance and pyrometer</td>
<td>Metal coated</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All dielectric</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>Multimode UV (200nm to 300nm)</td>
<td>Up to 300°C: Engine flame detector</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Fiber cable</td>
<td>Single and multifiber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Up to 200°C</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Above 200°C</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fiber bundle for pyrometer: up to 540°C</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Connectors</td>
<td>Up to 200°C</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Above 200°C</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Passive MUX/DMUX couplers</td>
<td>Up to 70°C in A/C bay</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Up to 125°C on engine with cooling</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>Up to 200°C on engine without cooling</td>
<td></td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>
Table 4. Needed Optical Component Development Status (Concluded).

<table>
<thead>
<tr>
<th>Sources</th>
<th>LED 600 to 1500nm</th>
<th>Laser Diode 800 to 1550nm</th>
<th>Xenon Tungsten (white)</th>
<th>PIN Diodes</th>
<th>Avalanche for sensitivity</th>
<th>Tungsten photocathode for UV sensitivity; up to 125°C</th>
<th>Effectors</th>
<th>Igniters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 70°C in A/C bay</td>
<td>Up to 125°C on engine for optical data bus</td>
<td>Up to 70°C in A/C bay</td>
<td>Silicon: 200 to 1000nm</td>
<td>Up to 70°C in A/C bay</td>
<td>Up to 70°C in A/C bay</td>
<td>Optically controlled, electrically powered torque motor</td>
<td>Optically controlled, optically powered torque motor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Germanium and InGaAs: 800 to 1600nm</td>
<td>Up to 125°C for on-engine optical data bus</td>
<td>Up to 70°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


handling forces. The outer sheath or sealing tube should be lightweight and stiff but flexible enough to facilitate installation.

5.1.3 Cable to Connector Interface

The exterior layers of the cable need to be fastened to the exterior of a connector at the cable ends while the fiber and the loose tube are inside. There is currently no combination of cable and connector that is qualified for the 200° C environment. Given the changes in length described above and the limits of shear strength of adhesives so far used, axial movement of the fiber within the contact (pistoning due to temperature cycling) has been an insoluble problem. The backshell strain relief must be long and supportive of the fibers to insulate the delicate fiber/connector interface from vibration.

Techniques in fusion splicing of optical fibers are rapidly improving. A completely fusion-spliced system is recommended on the airframe. Reliability would improve by eliminating connectors, but supportability would suffer. Such a system would use fused, replaceable lengths of fiber in each cable run.

5.1.4 Qualification-Tested Cables

At least two manufacturer's fiber optic cables have been successfully tested to the requirements (-55° to 125° C and 15 "g's" from 10 to 500 Hz) of MIL-STD-1760 Aircraft/Store Interconnection Standard System (Reference 1). Use on aircraft will require formulation of new standards.

5.2 OPTICAL FIBERS

Three environmental temperature ranges can be identified, as shown in Table 4. For typical sensor data communication, single multimode fiber with a 100 to 200 µm or larger core is recommended. Many glass and quartz fibers will withstand the lower temperature range, so sensor design will probably dictate the fiber size and numerical aperture. For temperatures above 200° C, the organic coatings on current fibers are a limitation. Borosilicate or metal-clad silica fibers are high-temperature candidates currently available.

5.2.1 Mode losses

Given the use of multimode fiber, a fiber type that is either larger in core diameter or numerical aperture (NA) will allow more energy to be launched. Launch efficiency is a concern with sensors that use extrinsic techniques such as reflection from a toothed wheel. Fibers with larger NA carry more modes at higher angles, but these are the first modes lost due to vibration, microbending, index change with temperature, and other phenomena. It is better to improve launch efficiency by using larger diameter fibers. Previous work has found that modal noise and detector efficiency is improved by underfilling the modal volume of transmission fibers (Reference 2).
5.2.2 UV Transmission

Some sensor techniques require transmission to wavelengths as short as 200 nanometers. This limits the choice of materials to silica or sapphire. Sapphire optical fibers of useful quality are not yet available, and even the more developed silica technology does not transmit enough for the distances involved.

It is suggested that a fluorescence technique may be useful to enable sensing of short wavelengths. There are currently available optical fibers that have an ultraviolet (UV) absorbing dye. The absorbed energy is released in photons of near 600-nm wavelength - transmissable through a much longer distance. A silica or sapphire fiber can receive UV energy in the thermally hostile area and transmit it a short distance, say one meter, to be connected to the fluorescent fiber, and then to conventional fiber back to the control.

5.2.3 Single-Mode Fibers

The vast majority of fiber optic sensors reported in the vendor survey do not require single-mode fiber. A promising sensor requiring single-mode fiber would have to be traded against characteristics of this fiber which are less desirable. The core of single-mode fiber is on the order of 5 to 10 μm, making connector tolerances on the order of 1 μm. Multimode fiber connector tolerances for equivalent insertion loss are at least an order of magnitude larger. Further, some sensors that use single-mode fibers would require the use of laser diode sources which are environmentally sensitive.

5.3 Fiber Optic Connectors

Presently, there are two styles of standard connectors which may be applicable to aircraft fiber optic systems, after some temperature-rating improvement. They are the best commercially available starting-point designs. The stainless steel SMA style, per MIL-C-83522 for single-fiber connections or small bundles, and the MIL-C-38999 style, with fiber optic inserts for multi-fiber cables, have advertised ratings to 71° and 125° C respectively. The UH-60A helicopter (Reference 3) uses a multifiber connector (Reference 4) meeting the requirements of MIL-C-28876, limited to 85° C. The materials used have the temperature resistance in themselves, but additional attention must be given to vibration, material expansivities, and oxidation resistance at temperature. Higher temperature range applications will likely require new designs.

5.4 Optical Sources

Optical source choices include light-emitting diodes (LED's), laser diodes, tungsten, xenon, and many others. The LED offers the best combination of reliability, power usage, and efficient use of space.
5.4.1 Reliability

LED's are currently available in standard Mil-Spec packages that can operate from 25\(^{\circ}\) to 125\(^{\circ}\) C with 3 dB of loss, covering a broader wavelength spectrum than laser diodes. Life at 125\(^{\circ}\) C is likely to be more than 10,000 hours. Operation at 180\(^{\circ}\) C has been demonstrated (Reference 5).

Compared to LED's, laser diodes are the more electrically efficient but use more power and have significantly shorter life. The upper temperature limit is about 70\(^{\circ}\) C without thermoelectric cooling. Tungsten sources are less efficient and less reliable than LED's but provide broadband wavelengths. Xenon sources are typically much larger and have the added complications of needing high voltages to start and creating EMI.

5.4.2 Available Spectra

LED's discontinuously cover a wavelength range from about 480 to 1550 nm. Laser diodes are commercially available from 780 to 1550 nm. Wavelengths shorter than 800 nm suffer significantly more transmission loss in optical fibers, and industry has not concentrated on speed, power, and fiber coupling for existing products in that spectral range. From 800 to 1550 nm, with currently available devices, six spectral channels may be used on one transmission fiber with good separation. Since temperature affects the optics that presently MUX and DMUX the channels, a range of -54\(^{\circ}\) to 125\(^{\circ}\) C would probably require about 20 nm of buffer distance between spectral channels (edge to edge) to prevent crosstalk. This channel spacing will improve to allow more channels per fiber.

5.4.3 Optical Power

Laser diodes can launch much more power into a fiber optic system than any other source. While source outputs will continue to improve, laser diodes will always have about a 10\(\times\) advantage because of the higher energy level and inherently narrow angular beam.

5.5 OPTICAL DETECTORS

Detector requirements are largely influenced by sensor design. Variables include different spectral regions, levels, sensitivities, and response times.

5.5.1 Solid State - Avalanche Versus PIN Diodes

Silicon PIN photodiodes have adequate sensitivity, speed, and linearity for most applications. They are less temperature sensitive, require less surrounding circuitry, and cost less than other candidates. Avalanche photodiodes can provide 100\(\times\) more sensitivity than the PIN type but require higher bias voltage levels and sacrifice linearity.
The best optically sensitive materials for solid-state detectors are silicon from 200 to about 1000 nm and germanium, indium gallium arsenide (InGaAs), or indium gallium arsenide phosphide (InGaAsP) from 800 to 1600 nm. Because optical sources have also been made in InGaAs, it will become possible to integrate sources and detectors for transmit/receive functions on the same substrate.

5.5.2 Tube Detectors

For extreme sensitivity at shorter wavelengths, a tube device may be considered. They are available in packages as small as 12-mm diameter with mechanics rugged enough to meet aircraft requirements. Tube-style detectors use a variety of photocathodes; the UV sensitive material required for flame detection is tungsten.

5.6 PASSIVE OPTICAL COMPONENTS

Passive optical components are used to direct optical energy among the various paths and are necessary for reducing control system cabling in the protocol branch architecture as described in Section 6.3. The distribution of energy can be determined by spectral content or the state of polarization, or the energy may simply be split at some ratio. Couplers can be made spectrally selective so that energy from several spectral sources is coupled to one transmission fiber to multiplex, and conversely to demultiplex, although temperature sensitivity is a limitation in aircraft applications. A coupler can combine energy between fibers in both directions. A tap can be used to monitor the energy within a fiber.

5.6.1 Coupler Types

Fused couplers place the cores of two or more fibers in proximity so that the evanescent waves couple energy between them. The distance between cores, indices of refraction, and length over which the coupling occurs control the amount of coupling and wavelength selectivity (Reference 6). One wavelength-selective device using the evanescent wave technique is made in integrated form of InGaAsP (Reference 7), offering the possibility of including spectral MUX/DMUX devices with the source and detector instead of separate components.

Couplers can also be made of bulk optic components scaled down to fiber optic compatible sizes. Taps, polarizing couplers, and spectral MUX/DMUX couplers have been made with small lenses and beam splitters. Often the lenses are of the graded index type. Another bulk optic style for spectral MUX/DMUX is made with a grating and reflective spherical surface (Reference 8). It is completely monolithic and can be made in quartz for temperature resistance. It is capable of multiplexing a large number of spectral channels with competitive efficiency.
5.6.2 Environmental Limits

The highest temperature capability available commercially is 125 °C for some couplers. Reference 9 describes the design of temperature-insensitive, single-mode couplers. Multimode types, with many more modes and broader spectral range, may not have that capability. The quartz grating/reflecter type mentioned above is likely to work at least to 125 °C. High ambient temperatures limit the usefulness of engine-mounted passive couplers. The fused couplers and the grating/reflecter types are expected to be resistant to engine vibration, but the beam-splitter/filter and graded-index lens styles will require close attention to mounting techniques.

5.7 EFFECTORS

Three options for a fiber optic effector are identified as follows:

1. Optically Controlled, Electrically Powered Torque Motor Driving a Hydraulic Actuator - Requires optic, electric, and hydraulic supply systems. Probably the best near-term approach because it uses conventional electrical torque motors and demonstrated high-temperature GaAs technology. Electrical cables/circuitry are present.

2. Optically Controlled, Optically Powered Torque Motor Driving a Hydraulic Actuator - Optic and hydraulic supply systems are required. Photovoltaic cells drive electrical torque motors. Electrical circuitry is present.

3. Optically Powered Direct Opto/Hydraulic Actuation - Candidate fluidic conversion techniques include:

   a. Photoacoustic Effect - Switching element is composed of optically active crystalline material with a large photo-acoustic coefficient; incident light energy changes the dimensions of the switching element, or pulsing incident light excites mechanical vibrations. Hydraulic energy can be switched among resonant-frequency-tuned output ports.

   b. Photothermal Shock - Very fast rise-time incident optical pulse generates a thermal shock wave that changes the state of a fluidic switch.


5.8 OPTICAL IGNITION

The high voltage and electrical fields associated with electric spark ignition on an aircraft engine could be produced by using optical energy to
excite ignition. Required energy per spark is estimated at one millijoule. This is electrically 1000 volts at one milliamp for one millisecond. A typical infrared-emitting diode can deliver one milliwatt of power, which means one second to achieve a millijoule. However, the energy comparison is not direct because of losses in efficiency between the optical output and the spark. The following are some possible theoretical approaches.

**Electrical-Field-Generated Spark** - Because light waves are time-varying electric fields, it is possible to create the field strength necessary to ionize air (create a spark). This has occurred as a nuisance in high-energy laser experiments. High-quality optics are required.

**Thermally Generated, High-Temperature Pulse** - A high-temperature source for ignition can be produced by directing a large-energy optical signal at a thermally well-isolated absorbing body. Absorption and conversion to heat can be 50% or more efficient.

**Photochemically Generated, High-Temperature Pulse** - An optical signal can be used to liberate chemical energy. The ignition source is the chemical reaction produced by irradiating a target of photoactive material. Also, a photoactive material could be added to the fuel or combustion chamber. A similar technique has been used for aircraft missile ignition.

**Direct Photoelectrical Conversion Generated Spark** - An optical signal can be converted to an electrical current with efficiencies up to 10%. High spark voltage could be transformed from a low-voltage, optically generated current. Alternatively, the current could be used to charge a capacitor until the voltage level required for a spark is reached. Circuitry near the combustor would be temperature limited, and the rate of optical energy deliverable currently falls short of requirements.
6.0 INTEGRATED FIBER OPTIC CONTROL SYSTEM

6.1 INTEGRATED AIRFRAME/PROPULSION CONTROL SYSTEM ARCHITECTURES (IAPSA) STUDY

An advanced fighter aircraft for the 1990's is postulated to require highly coupled and integrated flight and propulsion controls to achieve the needed mission performance and maneuver capability. Phase I of the IAPSA study (Reference 10) conducted by Boeing Military Airplane Company (NAS1-16942) investigated the benefits of integrated control system architectures for future high-performance aircraft. The following discussion summarizes the results of that study which influence the fiber optic control system chosen for the FOCSI study.

IAPSA examined and compared the features of six advanced architectures. Two architectures were chosen for detailed study: the distributed system (D/D) using modular construction and high-speed data buses for intersystem communication and the centralized/direct-connected system (C/D) using high-speed computers and optical technology to concentrate the electronics in centralized locations.

The IAPSA evaluation selected C/D architecture as having the greatest payoff in meeting 1990's supersonic military aircraft system requirements, as shown in Table 5. System maintainability and vulnerability were the most important factors. Low line-replaceable unit (LRU) count, due to integration and centralization of flight, engine, and inlet controllers, promoted high maintainability. Vulnerability to combat damage and EMI/EMP was minimized by low LRU count and optical technology. Low LRU count was also beneficial to reliability and life-cycle cost. C/D architecture posed a higher technical risk in the areas of fiber optics and fault-detection schemes; however, it was reported that sufficient lead time should resolve these issues.

Table 5. IAPSA Analysis Results (from Reference 10, p 6-23).

<table>
<thead>
<tr>
<th>Grading Area (Weighting)</th>
<th>Baseline</th>
<th>Distributed</th>
<th>Centralized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade</td>
<td>Weighted Grade</td>
<td>Grade</td>
</tr>
<tr>
<td>Reliability (3)</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Maintainability (2)</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Availability (2)</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Life-Cycle Cost (3)</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Flexibility (1)</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Computing Requirements (1)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Complexity (2)</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Vulnerability (2)</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>1990 Technical Risk (1)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Thermal Immunity (1)</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Weighted Total</td>
<td>31/18 = 1.72</td>
<td>36/18 = 2.00</td>
<td>49/18 = 2.72</td>
</tr>
</tbody>
</table>
The many benefits of low LRU count in a centralized system would be negated without the use of fiber optic sensing. In a centralized electrical system, sensors distributed throughout the aircraft would require long wiring harnesses that are unacceptable from a weight and (in composite aircraft) EMI/EMP standpoint. Fiber optic sensing is an enabling technology for a centralized system, especially if the protocol branch method of connecting the components is employed, as described in Section 6.3.

6.2 CENTRALIZED/DIRECT ARCHITECTURE

The total fiber-optic, integrated propulsion/flight control architecture concept chosen for FOCSI study is the centralized-computing/direct-connected or centralized/direct system, echoing IAPSA. A schematic of the architecture is shown in Figure 7. All of the electronic components are located in two central, cooled bays. All of the sensors and actuators are interfaced with optical fibers. Engine and airframe control surface actuators are optically controlled and hydraulically powered. A detailed discussion of the off-engine propulsion control is presented in Section 6.5.

In addition to the advantages described in the preceding general IAPSA conclusions, C/D architecture also provides the following benefits:

- Order of magnitude better electronics reliability.
- Maintenance interval determined by optical device reliability.
- Life-cycle cost driven by optical components and highly reliable electronics.
- Simpler environmental control system.
- Simplified electrical power distribution and interrupt protection.

6.3 PROTOCOL BRANCH METHOD

The variety of fiber optic sensor transmission protocols was described in Section 4.2.2. The multitude of options in specification of a complete fiber optic C/D system requires an efficient methodology to connect the optical protocol fibers directly from optical termination cards in the centralized bays to the sensors and/or actuators. By grouping the sensors on the aircraft into branch groups, the task of evaluating all the possible combinations is greatly reduced. Appendix B includes a description of how the protocol branch method relates to sensor selection.

The protocol method of optical system configuration begins with selection of candidate protocols that have the necessary robustness to survive the aircraft environment without loss of data integrity. Next, sensor/actuator functional groups are defined by location or task similarity; the issues of
Figure 7. FOCSI Centralized/Direct Architecture.
reliability and redundancy may also be addressed. Functional groups are then assigned to candidate protocols, defining protocol branches, and tradeoffs among protocol and device characteristics are evaluated. Reference 11 gives a step-by-step example of the protocol branch method as applied to the wing of an advanced fighter aircraft.

Each optical termination card in the centralized bays will support a single protocol and communicate with between 1 and 16 groups of devices, or branches, as shown in Figure 8. Each card converts the multiplexed optical protocol information coming in on the fiber into meaningful, compensated, linearized data going out on the computing system backplane.

6.3.1 Preliminary Protocol Branch Selections

The following chart shows protocol branch selections that have robustness necessary to survive in an aircraft environment and are currently supported by enough devices to make them feasible.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength-Referenced Intensity</td>
<td>• Good MUX-ability</td>
<td>• Limited Update Rate (Presently 10-200 kHz)</td>
</tr>
<tr>
<td></td>
<td>• Many Device Types</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• F-P Devices Very Accurate</td>
<td></td>
</tr>
<tr>
<td>TDM Code</td>
<td>• Fast Update Rate</td>
<td>• Delay Coil Bulky</td>
</tr>
<tr>
<td></td>
<td>• Excellent MUX-ability</td>
<td>• 1% Accuracy</td>
</tr>
<tr>
<td>WDM Code</td>
<td>• Very Fast Update</td>
<td>• Uses Broad Spectrum</td>
</tr>
<tr>
<td></td>
<td>• Small Devices</td>
<td></td>
</tr>
<tr>
<td>Pulse Rate</td>
<td>• Simple Devices</td>
<td>• Limited Device Types</td>
</tr>
<tr>
<td></td>
<td>• Rapid Update</td>
<td></td>
</tr>
<tr>
<td>Pulse Length</td>
<td>• Supports Midrange Temperature Sensor</td>
<td>• Limited Device Types</td>
</tr>
</tbody>
</table>

The wavelength-referenced-intensity protocol is an example that is highly multiplexable and supported by many devices. Figure 9 shows two examples of optical position sensor concepts using the wavelength-referenced-intensity protocol. Example A employs multiple wavelengths while example B uses only a single wavelength referenced to a constant wavelength. Appendix B describes in detail the most suitable decoding for optical sensors in the recommended far-term architecture. The optics of the receiver card may be implemented in a very general way with the use of a dispersive element, such as a corrected...
Figure 8. Protocol Branch Configuration Example.
Holographic diffraction grating separates input light into spectrum across face of code plate.

Input light

Code plate

Lens, or GRIN array

Wavelength coded bit receiving fibers

Fiber coupler/multiplexer

Input/output fiber

a) Position Sensor Using Wavelength Division Code Plate Decoding

Protocol interface card

Central Bay
Backpanel Bulkhead Bulkhead

I

\[ \lambda_1 \lambda_2 \lambda \]

WDM \( \lambda \) transmission bands

WDM 1:4

Backpanel Bulkhead

\[ \lambda_2 \text{ reflected} \]

\[ \lambda_1 \text{ reflected} \]

b) Position Sensor Using the Difference of Two Wavelengths Decoding

Figure 9. Examples of Sensors Using Wavelength-Referenced-Intensity Protocol.
holographic grating, and a dense linear array of photodiodes. These two components form an optical spectrum analyzer and provide information on the complete spectral content. This analyzer will support the following decoding capabilities:

- **Fabry-Perot Decoding**: Multiplexing is possible by differences in finesse. Many accurate sensor types are possible.

- **Wavelength 1 - Wavelength 2 Decoding**: Allows tracking spectral drift and broadening; capable of multiplexing 10 to 50 devices.

- **Wavelength Resonance Decoding**: Spectral gap shift; possible integrated optic sensor.

- **Peak Wavelength Shift/FM Decoding**: Grating distortion, birefringence.

- **Pyrometer Blackbody Temperature Decoding**: Possible to multiplex pyrometers by selecting pairs of infrared wavelengths for each, with each pair being separated by a μm of wavelengths.

- **Wavelength Division Code Plate Decoding**

### 6.3.2 Optical Tools for Protocol Branch

Optical systems and networks require different tools than those needed by electrical systems. Several general tools are already available: optical multimeters contain an LED and a detector to enable power, attenuation, and continuity measurements; optical spectrum analyzers reveal frequency content; fiber fusion splicers produce solder-like joints.

The protocol system requires specific tools currently not available. A sensor simulator attached to the optical fiber in place of any sensor could analyze sensor input light characteristics and provide sensor return light to evaluate conditions of the fiber branch and receiver card. A tool attaching to the fiber in place of a protocol receiver card could provide light to stimulate a sensor and to drive and analyze aircraft protocols including sensor output characteristics. A slot usage meter mounted in-line between the receiver card and the branch could analyze the occupancy of possible protocol ports, or slots. A fault simulator attaching at any optical port, or in-line with devices, would aid system checkout and verification by fault injection.

### 6.4 FLIGHT CONTROL SYSTEM DESCRIPTION

Using the protocol branch method, the F-18 flight control system can be configured into the following preliminary functional groups for a fiber optic control system:
### Group Redundancy Members Protocol

<table>
<thead>
<tr>
<th>Group</th>
<th>Redundancy</th>
<th>Members</th>
<th>Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rudder</td>
<td>2</td>
<td>Servocylinder, Rudder</td>
<td>$\lambda_1 - \lambda_2$</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Pedals, Rudder, Position</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Stick, Control, Pitch Position</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Stick, Control, Roll Position</td>
<td></td>
</tr>
<tr>
<td>Controls</td>
<td>1</td>
<td>Switches, Panel, Stick, Speed Brake, Wing Lock, Fold</td>
<td>$\lambda_1 - \lambda_2$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Actuator, Trim, Longitudinal Feel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Release, Ram Air Door</td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>4</td>
<td>Gyroscope, Rate</td>
<td>Pulse Rate, Width</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Accelerometer, Linear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Angle of Attack</td>
<td></td>
</tr>
<tr>
<td>Aileron</td>
<td>2</td>
<td>Servocylinder, Aileron</td>
<td>WDM Digital</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Servocylinder, Leading-Edge Flaps</td>
<td></td>
</tr>
<tr>
<td>Stabilator</td>
<td>4</td>
<td>Servocylinder, Stabilator</td>
<td>WDM Digital</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Servocylinder, Trailing-Edge Flaps</td>
<td></td>
</tr>
</tbody>
</table>

### 6.5 PROPULSION CONTROL SYSTEM DESCRIPTION

#### 6.5.1 Near Term

The near-term propulsion control system approach is directed toward aircraft implementation in the 1995 time frame, using technology that must be frozen by 1988-1989. The configuration for this study was defined to include an engine-mounted Full-Authority Digital Electrical Control (FADEC) with all engine-mounted sensors and cables remaining electrical. Possible exceptions are the pyrometer and/or light-off detector using fiber optics to eliminate the need for fuel-cooled sensor electronics. In addition, near-term optical position or speed sensors could be introduced to acquire engine-mounted experience.

The main difference from the present advanced engine configuration is communication between the engine and airframe through an optical data bus. This reduces the electromagnetic interference threat on the relatively long electrical cables and allows compatibility with an all-optic airframe but requires addition of an electrical/optic data bus coupler. Figure 10 shows this near-term approach applied to the F404 control system.

It may be possible to develop some optical sensors for near-term application, with the benefits of reduced cable weight and possibly reduced sensor complexity. However, since many of the sensors will not be ready, the full
Figure 10. F404 System Rollout for Near Term Fiber Optic Aircraft.
The benefits of a total fiber-optic, integrated C/D aircraft system will not be realized. Also, moving the FADEC to the aircraft bay is too drastic a change to occur in the next two to three years, since engine-mounted controls are predominant. Additionally, the mixture of supportability tools and addition of optical/electrical interfaces to the engine control make a part-electrical/part-optical system less favorable. The described near-term approach could serve as a test-bed for propulsion system optical components.

6.5.2 Far Term

The far-term propulsion system approach is directed at aircraft implementation and flight qualification in the year 2000 time frame and later. It takes advantage of airframe all-optical protocol branch architecture by moving the FADEC to the aircraft bay. Communication with the engine optical sensors is through engine-mounted optical couplers that must be developed to permit operation in high-temperature environments. Some possible protocol branch groupings for the F404 sensor set are as follows:

- Digital-pulse-coding branch: positions, liquid level
- Pulse-rate branch: speeds, flow, inlet temperature (pulse delay based on fluorescence decay)
- Wavelength-coded branch: pressures and switches
- Amplitude-variation branch: turbine temperature, flame detector, accelerometer
- Pulse-duration branch: torque motors and solenoids

Figure 11 shows the far-term approach applied to the F404 control system, with all sensors becoming optical. To demonstrate this kind of system on the F404 engine would require replacing all sensors, using the fuel control as only a fuel valve, reconfiguring the cable set with protocol couplers, and redesigning all computation for mounting in the aircraft bay.

The engine electronic control could now be conceived of as consisting of processor cards and protocol cards, mounted in an enclosed chassis or pod. It would be adjacent to and interface with the same power and data connections as other flight control cards through backplane electrical and optical connectors. It would be accessed only by an engine manufacturer technician.

6.5.3 Off-Engine FADEC Accountability

An engine-mounted propulsion control provides a complete propulsion system with a fully assembled and tested control system prior to aircraft installation. This assures fault isolation and accountability, thus avoiding airframer and engine manufacturer logistics problems. This has been the traditional approach throughout the propulsion industry.
Moving the propulsion control to the aircraft bay as a separate entity, in order to eliminate engine-mounted electronics, should not open up new approaches to control responsibility. The engine control and interface connections should remain essentially parts of the propulsion system, even though separated from the engine by fiber optics and integrated with the flight control computer. The propulsion system could still be independently tested using a flight control computer simulator.

Fully hardware-integrated fiber optic propulsion/flight control system concepts are described as embedding engine electronic control computation within the overall flight control. If justified by trade study results, a new approach to accountability must be formulated.

6.5.4 Pressure Transducer Location

A fully fiber optic integrated control system assumes moving the engine electrical control to the aircraft bay. Electrical pressure sensors are usually mounted in the on-engine control and connected with pneumatic tubing to the sensing site. The control chassis provides vibration isolation and a reduced-temperature environment. Time delay of the pressure signals precludes moving the sensors to the bay with the control electronics.

Engine mounting of the pressure transducers in a separate chassis that must be separately cooled increases life-cycle cost and decreases reliability by increasing system complexity. However, this is just the approach being strongly considered for advanced FADEC systems, even though the FADEC remains on the engine. With the number of pressure transducers on advanced engines, say 10 per channel, it is advantageous for allocation of computer time to provide them with a separate processor. In fact, they may turn out to be "smart" transducers. Also, a separate box for pressure transducers may more efficiently assign the roles of controls component designers and control computer designers.

Fiber optic pressure transducers, in a fully optical system, would not contain electronics. Normally, for electrical transducers, electronic compensation is performed within each transducer. It should not be assumed that fiber optic transducers need as much compensation as electrical transducers. A considerable part of electrical transducer nonlinearity is from temperature effects in the electronics themselves. In low-accuracy applications such as the F404, pressure transducers are mounted directly on the engine casing. It seems reasonable that fiber optic transducers without electronics may achieve acceptable performance. It remains to be seen, however, whether materials can be chosen for fiber optic pressure transducers to minimize temperature and other effects.

6.5.5 Addressing Off-Engine FADEC Issues

Studies have been performed to assess the advantages and disadvantages of on/off engine-mounted control locations (Reference 12). Results have shown
that engine-mounted control configurations are preferable. The emergence of optical technology is likely to impact control system design in the 1990's. This impact will justify reevaluation of the following on-engine versus off-engine control issues:

**Issue: Reliability** - Failures of aircraft supplied power and cooling to an off-engine control would cause loss of all engines.

**Response** - Present aircraft flight controls use highly redundant power and cooling supply configurations. Engine-generated power could be a secondary source. Failure of an on-engine control due to cooling loss would be more rapid.

**Issue: Reliability** - Reliability through multiple engines is compromised if engine control systems are combined in any way.

**Response** - The centralized aircraft control could be housed in at least two redundant, physically separated areas, each capable of controlling both engines.

**Comment** - Reliability of electronics mounted in the centralized, less hostile temperature and vibrational environment is significantly improved.

**Issue: Vulnerability** - A single localized aircraft control is vulnerable to a single battle-damage occurrence and loss of the total aircraft.

**Response** - Redundant central bays can be physically separated and located strategically.

**Issue: Vulnerability** - Longer control cables and additional connectors between the engine and bay are more vulnerable.

**Response** - The weight advantage of fiber optics can be translated to increased redundancy.

**Comment** - Optical cables should eliminate potential signal interference occurrences.

**Issue: Life-Cycle Cost** - On-engine control location shows significant reduction in recurring and acquisition cost of the control.

**Response** - From a total aircraft viewpoint, elimination of many LRU's in a centralized system should reduce LCC. The bay provides commonality and simpler cooling.

**Comment** - Lack of need for EMI shielding and lighter weight of optical fibers greatly reduces the weight penalty of sensor cables in a centralized system. Use of protocol branch method to multiplex signals further reduces weight.
7.0 PROPULSION SYSTEM TRADE STUDIES

7.1 TRADE STUDY PROPULSION SYSTEMS

Figure 12 shows five propulsion control systems for the trade study evaluation. They are intended to allow assessment of the major electrical/optical components as a system. They are not intended to imply a specific connection configuration. System A is the all-electrical baseline; systems B through E are alternate concepts to integrate with an all-optical airframe. Table 6 lists normalized weight/area estimates for each system based on an F404 on-engine cable set (six multibranched harnesses), present advanced FADEC programs, and recent fiber optic component design estimates.


<table>
<thead>
<tr>
<th>System</th>
<th>A *</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine-Mounted Control; Triplex Cable Set</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Engine-Mounted Triplex FADEC (A, C, and D) or Triplex Protocol Couplers (E)</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>1.2</td>
</tr>
<tr>
<td>Data Bus Couplers (A, C, and D)</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>Data Bus (A, C, D) or Interface Cables (B) or Protocol Cables (E)</td>
<td>1.0</td>
<td>1.0</td>
<td>20.0</td>
<td>6.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Flight Control Module (Including FADEC in B and E)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.3</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

System A is a baseline present FADEC system. The aircraft is assumed to be electrical. Data bus couplers are mounted on the thrust frame.

System B is the same as A except the FADEC is moved to the aircraft bay. FADEC is now in a less hostile environment. There is a large increase in cable area and weight between the engine and the aircraft bay.

42
Figure 12. Propulsion Control Systems For Trade Study.
System C is the same as A except there is an optical data bus between the engine and the aircraft bay. The long cables are now compatible with the optical airframe and weigh less.

System D is the same as C except all sensors/components/cables on the engine are optical. FADEC must grow to incorporate the optical/electrical conversion. On-engine cables are configured to take advantage of optical protocols and will weigh less.

System E is the all-optical approach with FADEC in the aircraft bay. Fiber optic protocol branches run between the engine and aircraft. Although similar in weight to the baseline FADEC, the three coupler channels do not intercommunicate and are easily separated to decrease vulnerability.

7.2 SUPPORTABILITY STUDY

7.2.1 Approach and Assumptions

Each system was evaluated relative to System A, the electronic baseline, in four major areas. The baseline system was assigned a nominal rating of 5 in all categories. For each proposed alternative system, a qualitative judgment in each category was made in comparison to the baseline. A higher value (>5) indicates a better evaluation; a lower value (<5) is worse.

One key assumption was that costs for fiber optic sensors, effectors, components, cables, and support equipment and reliability of fiber optic sensors, effectors, components and cable will eventually be comparable to those of current electronic items. Another assumption was that the aircraft bay is significantly less hostile in terms of temperature, vibration, and contamination and allows a lower weight design for the electronics than an on-engine location.

The results are shown in Table 7. A definition of each evaluated area and a discussion for each system evaluation versus System A follows.

7.2.2 Reliability

Operational reliability is relative capability of a system to function in terms of mean time between system inoperability. The Mean Time Between Maintenance Actions (MTBMA) was used to evaluate overall system reliability.

For System B, operational reliability is improved, but redundancy will already have driven the failure rate into the $10^{-7}$ to $10^{-6}$ events per flight hour regime, so improvement is negligible. The MTBMA for the FADEC will improve substantially, but additional cable complexity and length may degrade this somewhat.

Operational reliability is essentially the same for System C. The MTBMA will be reduced due to the addition of the data bus optical coupler. Optical
Table 7. Propulsion System Supportability Trade Study Results.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reliability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>MTBMA</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td><strong>Maintainability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooling/Support Equipment</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Skill Levels</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Repair Level</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Mean Time To Repair</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td><strong>Life-Cycle Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquisition</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Operation and Support</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

Cables to the flight control will be similar to electrical cables in terms of reliability.

System D has negligible impact on operational reliability. The MTBMA will be degraded because of the double optical conversion required in the FADEC and coupler. Additional circuitry is needed. Increased heat load will result from the larger power supplies required.

Negligible impact on operational reliability results from System E, but the MTBMA should be improved due to relocation of FADEC as in System B.

### 7.2.3 Maintainability

Areas evaluated include impact on tooling/support equipment, impact on required skill levels, impact on component repair level, and impact on Mean Time To Repair (MTTR). Base level engine repairs include removal and replacement of parts (down to, say, board level electronics) at the organizational level (outside) and intermediate level (inside), but no parts testing. The electronic controls parts testing and repair are done at the depot level.

System B presents no impact on tooling, support equipment, or skill levels required at the organizational level of maintenance. Component repair level will remain the same. The MTTR will improve since there are fewer cable connectors, and fault-isolation time will be reduced.
Additional support equipment and tooling are needed for flight line fault isolation for System C due to the optical cables and data bus to optical coupler. Also, optical test equipment will be required at the depot level. Additional skills will be required at all levels of maintenance to support both optical and electronic components. There will be no impact on component repair level. The MTTR will remain the same based on the assumption that trouble shooting time will be similar.

For System D, support equipment and tooling requirements are greater due to the use of a mix of electrical and optical components. Additional skills will be required to maintain optical components at all levels of maintenance. No impact will occur on component repair level or MTTR. Fault-isolation capability and timing are similar to System A.

System E tooling and support equipment will be similar to System A except that they are optical. Depot will still require electrical and optical repair skills, while base level will only require optical skills. Use of protocol branches will reduce cable/connector requirements which will reduce trouble shooting time. Repair levels for all components will remain the same.

7.2.4 Life-Cycle Cost (LCC)

Acquisition and Operation and Support (O&S) costs were evaluated for each system.

The incorporation of the FADEC into the flight control in System B will significantly reduce the acquisition cost due to commonality with the flight control in aspects such as cooling, power, and hardware. The increase in flight control costs will be small. Increase in cable costs due to additional length will be minimal in comparison with FADEC cost reduction. O&S cost will be lower due to reduction in MTBMA and MTTR.

System C acquisition cost will be impacted by the need for new support equipment to test optical cables and data bus optical couplers. Costs for the coupler and optical cables are assumed to be similar for the comparable electrical devices. O&S costs will increase due to reduced MTBMA.

The acquisition cost of System D will be similar to System C since additional tooling and support equipment will be required at each base. O&S cost will increase due to a significant increase in maintenance action rate.

System E incorporates the FADEC into the flight control system, reducing acquisition cost significantly. O&S costs will also be lower due to reduced maintenance event rate and MTTR.

7.2.5 Availability

The impact on engine availability was evaluated based on the MTBMA and MTTR evaluations. This is a qualitative estimate of the system impact on the
frequency and elapsed time of engine flight line maintenance actions. The
increased maintenance action rate for Systems C and D will have a negative
impact on engine availability. The reduction in maintenance action rate and
MTTR for Systems B and E will improve engine availability.

7.3 SURVIVABILITY/VULNERABILITY STUDY

7.3.1 Combat Effectiveness Potential

Survivability is part of the overall combat capability posture of a given
weapon system; other factors include performance, lethality, and availability.
The survivability of a weapon system is a function of the mission, threats,
susceptibility, and vulnerability of the particular aircraft. By definition,
survivability ($P_s$) is determined by the susceptibility ($P_h$) of being hit by a
threat mechanism and vulnerability ($P_{K/H}$) as in the following relationship:

$$P_s = 1 - (P_h \times P_{K/H})$$

For this study, susceptibility and vulnerability are specifically defined as
follows (MIL-STD-2089):

**Susceptibility** is the probability of being hit by a threat damage mech-
anism and is the sum of the threat density, target signature, and threat
effectiveness.

**Vulnerability** is the probability that, given a single-shot hit on the
engine by a damage mechanism, the engine will be damaged to a level which
causes sufficient performance degradation to classify the engine as killed.
Implicit with engine vulnerability is the probability that the aircraft will
abort due to engine failure resulting from a threat mechanism hit.

7.3.2 Susceptibility

The means of reducing susceptibility by the use of fiber optics falls
into three categories as follows:

1. Reducing EMI - Electromagnetic-interference-disturbed components may
result in aborted missions and reduced aircraft availability. Inherently
immune to EMI, fiber optics enhances aircraft operability, especially in the
normally heavy EMI environment on carrier decks and in flight.

2. Reducing Susceptibility to EMP - The effects of electromagnetic pulse
threats (directed-energy weapons or high-altitude nuclear events) are reduced
because there is little internal coupling of EMP energy to critical electronic
components.


3. Reducing EM Radiation Signature for Detection or Homing - The primary source of EM radiation useable for missile detection and homing comes from radio, radar equipment, and other powered sources. Fiber optic reduction of EM radiation sources would be small assuming a baseline of properly shielded and maintained electrical wiring.

7.3.3 Vulnerability

The primary survivability benefit of using fiber optics is in reducing overall aircraft vulnerability to threat damage. While the probability of hit is a function of the susceptibility factors, the probability that a kill mechanism (such as a gun projectile, warhead fragment, or blast) hits the engine or any critical component is a function of the location and protection of the components and the distribution of hits over the aircraft surface.

Fiber optics permits more latitude in engine control location on the aircraft. Additional vulnerability protection may be afforded by strategic placement of critical components. The effect of adding redundancy to engine control components enhances survivability by effectively eliminating critical components. Fiber optic weight savings can be traded for redundancy. Also, fiber optic cables can be routed through areas previously avoided, because of electrical hazards, resulting in shorter cable lengths.

Changes in presented area and resulting changed vulnerable area provided by study Systems A through E were small compared to the overall aircraft and made no significant change in vulnerability.
8.0 DEVELOPMENT PLAN

8.1 OPTICAL TECHNOLOGY

Figures 13 and 14 show schedules and cost estimates to ready optical sensor and component technology for implementation in advanced aircraft on a demonstrational basis. Costs shown are on a per sensor/component basis; components, once developed, can be used with any applicable sensor. The result would be flight-quality hardware. Admittedly, some sensors will be easier to develop than others, so the charts are meant to show typical values.

Present status within the six-year development plan for the various sensors/components is shown along the top of each chart. In general, it is based on the vendor survey responses. For example, there are many optical linear position sensor concepts under development, one of which has been packaged in an aircraft design (Reference 3). Optical lube debris sensors have received little attention. Unknown factors are those vendors who did not report their status, vendors who did not respond to the survey, and vendors who were not sent a survey.

8.2 OPTICAL SYSTEM

Figure 15 is a chart projecting milestones and cost for development of the integrated fiber optic control system described in Section 6.0. It covers the following steps towards completion of a flight test:

- **Sensor/component development** covers the work shown in Figures 13 and 14. Interdependent sensors and components must be developed in parallel.

- **Protocol branch sensor/actuator networks** should be constructed and evaluated. Protocol branch tools will assist the system development.

- **Optical system update studies** are needed to review technology status and current control system requirements.

- To evaluate aircraft/engine worthiness, each sensor and component should be placed in a test-bed demonstration. This would take the form of piggybacking on ground and flight tests.

- For eventual flight test implementation, an integrated control system must be designed in detail for a particular application. For the far-term approach described in Section 6.5.2, the engine-mounted control must be redesigned for protocol inputs and airframe mounting. This would include specifications, drawings, sets of hardware, special test items, procedures, and training.
Figure 13. Optical Sensor Development Schedule To Achieve Flight-Quality Hardware.
<table>
<thead>
<tr>
<th>Years</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>* Component concepts definition*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>$50K</td>
</tr>
<tr>
<td>* Component concepts development*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>$150K</td>
</tr>
<tr>
<td>* Component concepts demonstration*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>$100K</td>
</tr>
<tr>
<td>* Prototype fabrication and testing*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>$1000K</td>
</tr>
<tr>
<td>* Aircraft design packaging*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>$300K</td>
</tr>
<tr>
<td>* Design assurance testing*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>$300K</td>
</tr>
</tbody>
</table>

Figure 14. Optical Component Development Schedule To Achieve Flight-Quality Hardware.
<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sensor development</td>
</tr>
<tr>
<td>2</td>
<td>Component development</td>
</tr>
<tr>
<td>3</td>
<td>Protocol branch and tool development</td>
</tr>
<tr>
<td>4</td>
<td>Optical system update studies</td>
</tr>
<tr>
<td>5</td>
<td>Test bed demonstration of optical hardware</td>
</tr>
<tr>
<td>6</td>
<td>Integrated control system detailed design for particular application (hardware)</td>
</tr>
<tr>
<td>7</td>
<td>Integrated control system bench test</td>
</tr>
<tr>
<td>8</td>
<td>Optical engine ground test</td>
</tr>
<tr>
<td>9</td>
<td>Integrated system ground test</td>
</tr>
<tr>
<td>10</td>
<td>Integrated system flight test</td>
</tr>
</tbody>
</table>

$25.0M$  
$17.0M$  
$3.0M$  
$1.0M$  
$5.0M$  
$25.0M$  
$5.0M$  
$5.0M$  
$10.0M$  
$5.0M$  

$101.0M$

Figure 15. Far-Term Integrated Optical System Milestone Chart.
• An integrated control system bench test is used to operate all the designed hardware in the laboratory under simulated aircraft inputs.

• The optically configured engine must be ground tested before being assembled to the airframe. Airframe communication would be simulated.

• The selected airframe must be configured with the integrated optical flight/propulsion control system and ground tested.

• Integrated optical flight/propulsion control system flight test.
9.0 CONCLUDING REMARKS

The subject of this report concerned the definition and evaluation of a total fiber-optic, integrated propulsion/flight control system, the component parts of such a system along with development status, and plans to implement the system on future advanced fighter aircraft.

A wide variety of sensors was shown to compose the propulsion and flight control system measurement set. The requirements comprise many ranges, high accuracy, and harsh environment. A fiber optic sensor survey indicated that, while all sensor categories received responses, almost all are in some need of development. Classification of fiber optic sensors by transmission method (communication protocol) was introduced as an aid to system design.

Requirements and recommendations were given for fiber optic circuit components. All-dielectric, high-temperature fiber (if needed), passive couplers, and high-temperature cable-to-connector interfaces most need development for the high-temperature engine environment.

A total fiber-optic, integrated propulsion/flight control system was described based on previous integrated architecture studies as well as the protocol method of efficiently connecting system components to centralized bay electronics. In terms of propulsion system supportability and vulnerability, study results show that fiber optics enable the favorable relocation of the engine electronic control in the aircraft bay. Considerable weight savings are expected on the airframe, but these were not specifically addressed.

Up to six years of development is forecast to ready fiber optic sensors and components for aircraft application. Another four years is projected to design and build an integrated control system and complete a flight test.
APPENDIX A

FIBER OPTIC VENDOR QUESTIONNAIRE

AND

VENDORS SURVEYED
Fiber Optic Sensor Vendor Survey Questionnaire Form

Please copy this form for each device or version of devices.

Name of device

Parameter sensed: _Temperature _Position, Linear _Lube Debris
_Pressure _Position, Angular _Pyrometer
_Flow, Mass _Velocity, Linear _Blade Tip Clearance
_Flow, Volume _Velocity, Angular _Flame
_Liquid Level _Acceleration, Linear _Other

Device Status: (estimated year)
Research Prototypes Available Development Mil-Qualified

<table>
<thead>
<tr>
<th>Range, operational</th>
<th>Range, damage limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy, % full scale</td>
<td>Linearity</td>
</tr>
</tbody>
</table>

Device Specifications

<table>
<thead>
<tr>
<th>Hysteresis</th>
<th>Precision, % full scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time constant (63.2%)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Size and Mass</th>
<th>Sensor head</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditioning E/O</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental Limits:</th>
<th>Operationally accurate</th>
<th>Max.</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration (duration)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Random freq., 6 g's</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinusoidal, 20 g's, 2000Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration shock, level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonant freq.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to aerospace fluids (1st)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condensation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immersion</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interfacing technique, or protocol (wavelength shift, analog level, etc.)

Please attach a basic schematic of device and interface: (block diagram)

Contact: Name ___________________________ Phone ___________________________
<table>
<thead>
<tr>
<th>Vendor</th>
<th>City</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accufiber Co.</td>
<td>Vancouver</td>
<td>WA</td>
</tr>
<tr>
<td>Amphenol Products, Lisle</td>
<td>Lisle</td>
<td>IL</td>
</tr>
<tr>
<td>Aster</td>
<td>Medfield</td>
<td>MA</td>
</tr>
<tr>
<td>AT&amp;T Technologies, Holmdel</td>
<td>Holmdel</td>
<td>NJ</td>
</tr>
<tr>
<td>Babcock and Wilcox Alliance</td>
<td>Alliance</td>
<td>OH</td>
</tr>
<tr>
<td>Brandenburger and Co., Palo Alto, CA</td>
<td>Palo Alto</td>
<td>CA</td>
</tr>
<tr>
<td>Collimated Holes, Inc., Campbell, CA</td>
<td>Campbell</td>
<td>CA</td>
</tr>
<tr>
<td>Comar, Inc.</td>
<td>Richardson</td>
<td>TX</td>
</tr>
<tr>
<td>Computer Genetics Corp., Wakefield, MA</td>
<td>Wakefield</td>
<td>MA</td>
</tr>
<tr>
<td>Consolidated Controls, Bethel, CT</td>
<td>Bethel</td>
<td>CT</td>
</tr>
<tr>
<td>Conax Buffalo Corp., Buffalo, NY</td>
<td>Buffalo</td>
<td>NY</td>
</tr>
<tr>
<td>Corning Glass Works, Corning, NY</td>
<td>Corning</td>
<td>NY</td>
</tr>
<tr>
<td>Cuda Products Corp., Jacksonville, FL</td>
<td>Jacksonville</td>
<td>FL</td>
</tr>
<tr>
<td>Cutler-Hammer Products, Milwaukee, WI</td>
<td>Milwaukee</td>
<td>WI</td>
</tr>
<tr>
<td>Develco</td>
<td>San Jose</td>
<td>CA</td>
</tr>
<tr>
<td>Diaguide, Inc.</td>
<td>Fort Lee</td>
<td>NJ</td>
</tr>
<tr>
<td>EG&amp;G</td>
<td>Salem</td>
<td>MA</td>
</tr>
<tr>
<td>Electro Corp.</td>
<td>Sarasota</td>
<td>FL</td>
</tr>
<tr>
<td>ELDEC Corp.</td>
<td>Bothell</td>
<td>WA</td>
</tr>
<tr>
<td>EOTEC Corp.</td>
<td>West Haven</td>
<td>CT</td>
</tr>
<tr>
<td>Ericsson Lightwave Cable Overland Park, KS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber optic Systems, Inc., Simi Valley, CA</td>
<td>Simi Valley</td>
<td>CA</td>
</tr>
<tr>
<td>Force, Inc.</td>
<td>Christiansburg</td>
<td>VA</td>
</tr>
<tr>
<td>Fort Fiber Optics, Newport Beach, CA</td>
<td>Newport Beach</td>
<td>CA</td>
</tr>
<tr>
<td>FSI</td>
<td>Lombard</td>
<td>IL</td>
</tr>
<tr>
<td>Fujikura Ltd.</td>
<td>Pittsburgh</td>
<td>PA</td>
</tr>
<tr>
<td>Furukawa Electric Co.</td>
<td>New York</td>
<td>NY</td>
</tr>
<tr>
<td>Galileo Electro-Optics</td>
<td>Sturbridge</td>
<td>MA</td>
</tr>
<tr>
<td>General Electric Co., AEG</td>
<td>Cincinnati</td>
<td>OH</td>
</tr>
<tr>
<td>General Electric Co., AID</td>
<td>Wilmington</td>
<td>MA</td>
</tr>
<tr>
<td>General Electric Co., CR&amp;D</td>
<td>Schenectady</td>
<td>NY</td>
</tr>
<tr>
<td>GE Electronics Lab</td>
<td>Syracuse</td>
<td>NY</td>
</tr>
<tr>
<td>General Fiber Optics, Inc.</td>
<td>Cedar Grove</td>
<td>NJ</td>
</tr>
<tr>
<td>General Motors Res. Labs</td>
<td>Warren</td>
<td>MI</td>
</tr>
<tr>
<td>Gould Research Center</td>
<td>Rolling Meadows</td>
<td>IL</td>
</tr>
<tr>
<td>Gulton Industries</td>
<td>Costa Mesa</td>
<td>CA</td>
</tr>
<tr>
<td>Hewlett Packard</td>
<td>Palo Alto</td>
<td>CA</td>
</tr>
<tr>
<td>Honeywell, Inc.</td>
<td>Plymouth</td>
<td>MN</td>
</tr>
<tr>
<td>Hughes Research Lab</td>
<td>Malibu</td>
<td>CA</td>
</tr>
<tr>
<td>Infrared Fiber Systems</td>
<td>Silver Spring</td>
<td>MD</td>
</tr>
<tr>
<td>ITT Electrooptical Prod.</td>
<td>Roanoke</td>
<td>VA</td>
</tr>
<tr>
<td>Kaptron, Inc.</td>
<td>Palo Alto</td>
<td>CA</td>
</tr>
<tr>
<td>Land Turbine Sensors, Inc</td>
<td>Tullytown</td>
<td>PA</td>
</tr>
<tr>
<td>Litton Fiber Optic Products</td>
<td>Blacksburg</td>
<td>VA</td>
</tr>
<tr>
<td>Luxtron Corp.</td>
<td>Mountain View</td>
<td>CA</td>
</tr>
<tr>
<td>McDonnell Douglas Astron. Co.</td>
<td>Huntington Beach</td>
<td>CA</td>
</tr>
<tr>
<td>Mechanical Technology, Inc.</td>
<td>Latham</td>
<td>NY</td>
</tr>
<tr>
<td>Omron Electronics, Inc.</td>
<td>Schaumburg</td>
<td>IL</td>
</tr>
<tr>
<td>OPCOA, Inc.</td>
<td>Santa Anna</td>
<td>CA</td>
</tr>
<tr>
<td>Optech, Inc.</td>
<td>Herndon</td>
<td>VA</td>
</tr>
<tr>
<td>Optelecom, Inc.</td>
<td>Gaithersburg</td>
<td>MD</td>
</tr>
<tr>
<td>Optical Sensors Inc.</td>
<td>Colchester</td>
<td>VT</td>
</tr>
<tr>
<td>Parker Berres</td>
<td>Irvine</td>
<td>CA</td>
</tr>
<tr>
<td>Parascientific, Inc.</td>
<td>Redmond</td>
<td>WA</td>
</tr>
<tr>
<td>Rosemount, Inc.</td>
<td>Egan</td>
<td>MN</td>
</tr>
<tr>
<td>Scientific Technology</td>
<td>Mountain View</td>
<td>CA</td>
</tr>
<tr>
<td>Simmons Precision</td>
<td>Norwich</td>
<td>NY</td>
</tr>
<tr>
<td>Skan-A-Matic</td>
<td>Elbridge</td>
<td>NY</td>
</tr>
<tr>
<td>Square D</td>
<td>Pinellas Park</td>
<td>FL</td>
</tr>
<tr>
<td>Statham</td>
<td>Oxnard</td>
<td>CA</td>
</tr>
<tr>
<td>Teledyne Gurney</td>
<td>Troy</td>
<td>NY</td>
</tr>
<tr>
<td>Teledyne Ryan Electronics</td>
<td>San Diego</td>
<td>CA</td>
</tr>
<tr>
<td>Vanzetti Systems, Inc.</td>
<td>Stoughton</td>
<td>MA</td>
</tr>
<tr>
<td>Vibrometer Corp.</td>
<td>Billerica</td>
<td>MA</td>
</tr>
<tr>
<td>Welch Allyn Inc.</td>
<td>Skaneateles Falls</td>
<td>NY</td>
</tr>
<tr>
<td>York Technology</td>
<td>Princeton</td>
<td>NJ</td>
</tr>
<tr>
<td>Outside USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arel Control Ltd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yavne, Israel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>British Marine Tech. Ltd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>London, England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canadian Instr. &amp; Res. Ltd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mississauga Ont., Canada</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canstar Communications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ontario, Canada</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta Controls Ltd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. Molesey, Surrey, England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focal Marine Ltd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedford, Nova Scotia, Canada</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fugitsu Laboratories</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kawasaki, Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optronics Ltd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge, England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piessy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kingsthorpe, Northampton, England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polytech GmbH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaisruhe, West Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolls Royce</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Derby, England</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sumitomo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokyo, Japan</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Protocol Branch Method and Sensor Selection

The protocol branch innovation is a concept, or method, that allows the efficient creation of multiplexed analog systems of fiber optic sensors and actuators. Central to the method is the distinction, in any real sensing device, between the transduction technique and the data transmission technique, or protocol. Ideal availability of a completely filled selection matrix of sensors supporting all combinations of the two would allow the most flexible sensing system architecture definition.

Every optical sensor type, such as pressure, temperature, or vibration, will employ one or several possible techniques to transduce the measured parameter into an analog optical signal. This signal will be transmitted along an optical fiber using 1 of approximately 12 data-transmission techniques or protocols. In many actual sensing devices, the selection of transduction technique absolutely determines the transmission method, but in others several options are available. Conversely, the selection of transmission technique does not rigidly constrain the transduction options. The protocol branch method exploits the possibility of independent selection of each quality for each device in the system. At present, the matrix of devices indexed by these two parameters is rather sparsely populated, so the method is of limited usefulness. However, as the available devices increase in number and flexibility, the matrix will fill, and use of an optimization procedure like the protocol branch method will become essential.

Consider the play of variables in the definition of a fiber optic sensing system: givens include the parameters that will be sensed, the length of the fiber runs, the required update rates, necessary accuracy, and environmental limitations. For example, there are currently several different fiber sensors for temperature, all with good accuracy and robustness. The selection of one over the others will then depend primarily on whether it is data compatible on a multiplexed network of other sensors. All other things being equal, sensor types that are easily multiplexable will be preferred over those that require dedicated fibers. Those that will multiplex with other types of sensors, say pressure, will be even more preferable. But now, which pressure sensors to choose? There are, again, several options of transduction technique and transmission protocol. Adding the position sensors, the limit switches, the vibration sensors, and others will increase the complexity of the selection process to the point of impossibility for the unaided human to arrive at an optimum solution. The protocol branch method provides a procedure to obtain a near ideal combination of variables.

One of the important benefits of adopting the protocol branch method is that it will drive sensor design in the direction of filling the matrix of device types. The holes, or missing pieces in the complete family, will become more apparent. When the sensor designers and inventors have a clear
understanding of this matrix, the separability of the two qualities, and an appreciation of the protocol branch benefits, a significant change in their design philosophy may take place. This will result in greater acceptance and use of the fiber optic technology due in part to the improved ability to tailor a new fiber optic sensor system to exact requirements.

**FOCSI Protocol Branch Selection**

Of the 12 identified techniques for transferring analog optical data from a sensor to the interface card, or from the card to an effector, only a few are currently suitable for serious use in aircraft systems of sensors and effectors, or actuators.

The preferred protocol is the two-wavelength-referenced analog level. In this technique, one wavelength carries the information in analog intensity level, referenced not to absolute light or dark levels but to an accompanying reference wavelength intensity level. These two wavelengths travel the same fiber path, encounter the same connectors, experience the same random loss mechanisms, and arrive at the optical terminal card equally attenuated. The ratio of the two levels will contain the information while the absolute levels may vary at random. This decoding technique is capable of handling several existing sensors, including linear- and angular-displacement devices, as well as pyrometric temperature sensors which take a ratio of two wavelengths for a blackbody calculation.

This multiwavelength protocol is feasible because of the development of the diode array photodetector and is greatly improved with the use of a holographic diffraction grating. These two elements very handily combine with fiber optics to allow easy spectral analysis of the guided light. An optical-to-electrical conversion card built with these two elements will have an unusually broad range of sensor communication protocol capability.

Previous implementation of this technique employed two photodetectors with wavelength filters to perform the discrimination. This approach, while simple, has several significant flaws including errors due to source wavelength drift and filter center wavelength shift, from age or temperature effects, and sheer number of optical components needed to multiplex several devices. Each channel requires a beamsplitter, two optical filters, and two detectors, as well as a means to tap some power off the multiplexed fiber. Each channel detection set steals optical power from all the other channels because the power division, or distribution, takes place prior to the wavelength separation.

Our approach is to perform the wavelength pair separation first with an optically dispersive element, preferably a holographic diffraction grating. Detection will be by an array of photodetectors on a single substrate. This grating-array (GA) technique offers several advantages including: improved distribution of individual-channel optical energy to the correct channel detectors, greater energy efficiency, simpler optical arrangement, ability to compensate for wavelength shifts, and ability to decode several sensor types.
The multiwavelength GA protocol decoding technique is one of the most capable, robust, and straightforward to implement. It is recommended as the optical-to-electronic interface for virtually all optical sensors in the FOCSTI architecture. The principal drawback of the technique is the 10 to 200 kHz response rate, making it possibly unsuitable for turbine-speed sensing by pulse counting. The technique is capable of interpreting and converting several different optical data-transference protocols, making it one of the most flexible techniques available, and requires a simple optical arrangement, making it feasible for development for use in a harsh environment.
REFERENCES


REPORT DISTRIBUTION

NASA Lewis Research Center
Attn: Robert J. Baumbick (MS 77-1)
21000 Brookpark Road
Cleveland, OH 44135 (20)

George Derderian (Code 310E)
NAVAIR Systems Command
Washington, DC 20361 (1)

Chuck Miesner (MS 473)
NASA Langley Research Center
Hampton, VA 23665 (1)

Jet Propulsion Lab
4800 Oak Grove Dr.
Pasadena, CA 91109
Attn: Ramon DePaula (1)

Mr. Paul Polishuk
IGI Consulting, Inc.
214 Harvard Ave.
Suite 200
Boston, MA 02134 (1)

Douglas Aircraft Co. (IMC 36-41)
3855 Lakewood Blvd.
Long Beach, CA 90846
Attn: J.R.S. Findlay (1)

MIT
77 Massachusetts
Attn: Dr. Alan Epstein
Rm 33-111
Cambridge, MA 02139 (1)

MIT
77 Massachusetts
Attn: Dr. Lena Valavani
Rm 33-111
Cambridge, MA 02139 (1)

Jim McPartland (Code 6012)
NAVAIR Development Center
Warminster, PA 18974 (1)

Andrew Glista (Code 330E)
Commander
NAVAIR Systems Command
Department of the Navy
Washington, DC 20361 (1)

Director
Army Applied Technology Lab
Code SAVDL-ATL-ATP (Roger Ferguson)
Fort Eustis, VA 23064 (1)

Commander
AFWAL/POTC (Les Small/Steve Prizbilko)
Wright-Patterson AFB, OH 45433 (1)

Russ Vizzini (PE 32)
Commander
NAVAL Air Propulsion Center
P.O. Box 7176
Trenton, NJ 58628 (1)

L.M. Hiblen (MS 500-211)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135 (1)

Department of the Army
DAVL-ATL-ATA (Joe Terry)
Ft. Eustis, VA 23604 (1)

Rod Katz (Code 8-11)
NAVAL Avionics Center
6201 E. 21st Street
Indianapolis, IN 46218 (1)

Carl Lorenzo (MS 77-1)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135 (1)

Bruce Lehtinen (MS 77-1)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135 (1)

Gary Seng (MS 77-1)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135 (1)

Norm Wenger (MS 77-1)
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135 (1)