Integrated and Distributed Position Navigation and Timing (PNT) Data in Shipboard Environments

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***Abstract* - The information and communication requirements of 21st Century Navies present dynamic and demanding challenges in the critical area of distributed and synchronized navigation and timing. Information must be integrated from diverse sources and be widely and easily distributed to user systems and platforms while maintaining integrity and security. The Navigation Sensor System Interface (NAVSSI) is a system that continues to expand to meet such ever increasing and demanding ship navigation and war fighting information requirements of today and tomorrow's United States and Foreign Military Sales (FMS) navies.**

NAVSSI is the pre-eminent source of precise, real-time, integrated Position, Navigation, and Timing (PNT) data for the United States and Spanish navies with Japan and South Korea scheduled to receive systems in the near future.

NAVSSI is designed to integrate the inputs from various navigation sensors and distribute the integrated navigation solution to shipboard weapon and combat support systems. Since NAVSSI gathers inputs from different shipboard sensors and then distributes the resulting navigation data, it has many "user interface" systems that receive the data. These users have stringent requirements for navigation and timing accuracy. In order to provide a highly accurate and robust navigation solution, NAVSSI has implemented the Navigation Source Integration (NSI) algorithm. This algorithm is based on the integration of the best sources of navigation data (generally GPS and INS). In addition, NAVSSI outputs four different time forms with accuracies between one hundred nanoseconds and ten milliseconds depending on user interface system needs.

As a result of higher levels of integration and interoperability requirements, Network Centric Warfare (NCW) has introduced new technological challenges, where once stand-alone systems are now networked together and therefore pose new security issues such as cross-domain connectivity. NAVSSI as a single common source of distributing PNT data on board Navy surface ships, faces the Information Security (IS) challenge of connecting to both classified and unclassified security domains. The strict timing requirements of PNT data, further constrain the scope of available IS products that can be deployed while maintaining these security boundaries. While the US Navy has specified that unclassified PNT data can cross from Black unclassified domain to Red classified domain, NAVSSI has the responsibility to ensure that it cannot be used to transfer other than PNT data, or provide connectivity for other types of networking and data communication services.

This paper will discuss how the NAVSSI implementation satisfies the requirements for computing timely, integrated and accurate PNT data, its distribution, and means for maintaining security.

I. INTRODUCTION

NAVSSI integrates data from various navigation sensors and distributes the integrated navigation solution, precise time and frequency data to shipboard weapon, combat support, command and control, communications, and training systems. NAVSSI also provides the ship's navigation team with dedicated workstations to plan and monitor ship maneuvers on National Geospatial-Intelligence Agency (NGA) Digital Nautical Charts (DNCs). NAVSSI utilizes open systems architecture, Government Off The Shelf (GOTS) software and Commercial Off The Shelf (COTS) software and hardware to reduce development costs [1].

NAVSSI is an Evolutionary Acquisition (EA) program that is continuing with its fifth phase - the development of Block 4 hardware and software. NAVSSI Block 0 and Block 1 systems were deployed throughout the surface fleet and replaced with Block 2 and later Block 3 systems. Block 3 and Block 4.2.0 systems are now being fielded throughout the fleet, while Block 4.2.1 is nearing completion with a new navigation distribution SubLAN architecture. The new version will increase the number of user systems supported and further expand the navigation tools available to the ship's navigation team.

The basic components of NAVSSI are the Real Time Subsystem (RTS) and the Display and Control Subsystem (DCS). The RTS integrates data from both an embedded Global Positioning System (GPS) receiver and external navigation sensors. It then distributes real-time precise navigation, time and frequency data to shipboard users. The DCS provides the capability to control the RTS, display the Ownship's navigation sensor information, display Digital Nautical Charts (DNCs), conduct voyage planning and route monitoring, and log navigation data [2].

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The NAVSSI Remote Station (NRS) provides the ship's crew with one or more networked workstation positions with similar capabilities to the DCS, without the directly attached peripheral devices.

Communications between the various NAVSSI subsystems and workstations are conducted over a redundant dual homed Local Area Network (LAN). Depending on the particular installation, this may be an internal NAVSSI LAN, or include a navigation data distribution LAN.

NAVSSI Electronic Navigation can be performed on the Block 4.2.1 system using the department of Defense (DoD) Common Operating Environment (COE) and the United States Coast Guard's (USCG) Command, Display and Control (COMDAC) Integrated Navigation System (INS), which is an integrated Command and Control (C2) Navigation Mission Application developed for the COE [1]. Some vessels have the Northrup Grumman Inc., Integrated Bridge System (IBS), which gets its PNT data from a NAVSSI distribution interface. Details of the NAVSSI Electronic Navigation capabilities will not be covered in this paper.

II. REAL TIME SUBSYSTEM (RTS)

The NAVSSI RTS receives input data from multiple sensors, which it processes into real time output of integrated navigation solution of PNT data for multiple user systems. Sensor input data is accepted and processed by the RTS in a variety of formats as shown in TABLE-I.

TABLE-I: SUMMARY OF BLOCK 4 DATA INPUTS

System[3]	Message Rate (Hz)[1]	Data Received
RTS to RTS	50[2]	All Sensor Data, IRIG-B, HaveQuick, 1PPS, Auto Switch Control
DCS/NRS	1	All Sensor Data, Control, Config., Lever Arms, Etc.
ADMACS	1	Wind Speed and Direction
Gyrocompass	Continuous	Attitude
AN/WSN-7 Synchro	Synchro	Attitude
DWIMS	10	Relative Wind, Speed, and Direction
MK-86 GFCS	1	Grid Identifier
AN/WSN-7 GPS/010	4	PVT, Attitude, Rate, $Speed_{Water}$ Performance
AN/WSN-7 Superchannel	50[2]	PVT, Attitude, Rate, $Speed_{Water}$ Performance
BFTT	1	Training Data
AN/WSN-8 DEML	8	$Speed_{Water}$
DMS/FODMS	10[2]	INS, Fathometer, Wind, Propulsion
AN/WQN-2(V) DSVL	8	$Speed_{Water}$, or Speed
EM Log	Continuous	$Speed_{Water}$
Fluxgate Compass	1	Heading, Magnetic
FOAL Receiver	Continuous	RF Input
GVRC	1	PVT, Status, Almanac
Ship's Network	Aperiodic	Leap Second Notification Request (ID18)
ICAN	Wind at 10 Std. Msg. at 50	Wind Speed and Direction, Nav. Msg. (OD19)
IP-1747 AN/WSN-7	0.125	AN/WSN-7 Control
MK-38 and MK-39 Aegis Clock Converter	1024	Aegis Combat System Time
GAS-1 Anti-Jam GPS Antenna	0.1	AGC, Firmware Version, Status
MK-105 and MK-106 ACEG	1024	Aegis Combat System Time
Synchro Wind	Continuous	Wind Speed and Direction
AN/UQN-4/4A	1	$Depth_{Keel}$

1 Data rates are approximate.

2 Multiple messages with highest rate given.

3 "AN/" has been omitted from many system titles in order to accommodate table constraints.

III. INPUT DATA INTEGRITY CHECKING

NAVSSI continuously monitors the data inputs from each source listed in TABLE-I to ensure data integrity. Integrity checking consists of, but is not limited to ensuring proper reception of data over the physical medium connecting the source to NAVSSI. Incomplete messages, messages with incorrect checksum errors, etc., are processed as specified in the appropriate Interface Design Specification (IDS). As required, NAVSSI posts visible alerts to the operator.

Message level validity checking is conducted based on source validity indicators transmitted with the data, if the IDS provides for such indicators. Sources indicating invalid data are not used by NAVSSI until the data are again marked valid by the source.

NAVSSI provides navigation data validity monitoring, consisting of continuous monitoring of the time evolution of each position source's error characteristics. If estimates in the source's error consistently fall outside of the source's statistical performance bounds, the source is marked as invalid. The source integration algorithm does not use this data and NAVSSI posts a visible alert to the operator. If a NAVSSI operator manually selects a source that is out of its performance bounds, NAVSSI displays a warning message to the operator.

IV. NAVIGATION DATA OUTPUT

NAVSSI provides the NSI algorithms that integrate the input data received from GPS with available Inertial Navigation System (INS) data to produce a highly accurate and robust navigation solution for position and velocity. The algorithms written to perform NSI take into account the error characteristics associated with each navigation sensor system and will meet the accuracy requirements specified in TABLE-II.

The RTS will update its estimation of position upon receipt of "Best" velocity data. Upon receipt of a GPS position update (from either GPS), the RTS will perform an integration of position using up to two GPS receivers and the best INS. Best INS is defined as the INS that is outputting position closest to the GPS over time. Velocity is calculated by smoothing the difference between the best INS and GPS velocities. The INS velocity is then corrected with this difference and used for NSI computations. A maximum ship's speed of 40 knots is assumed. When only INS data is available, NAVSSI tracks the accuracy of the INS.

For position, an integrated solution is calculated using data from one or two GPS receivers and from one or two INS units. This integrated position data is interpolated in a manner similar to dead reckoning between GPS fixes, using best INS velocities. This method provides a relatively smooth and accurate output of position with minimal latency to data users. When GPS is not available, NAVSSI accuracies are equivalent to the INS.

The source integration algorithm for position enables NAVSSI to provide appropriately referenced latitude and longitude that is accurate to within 12 meters (two dimensions, one sigma) under non-casualty conditions. This accuracy requirement is significantly more stringent than current requirements for INS. The accuracy requirement is based upon a Root-Sum-Square (RSS) of all known error components including the worst-case latency related error for each of the interfaces.

Attitude and attitude rate is not calculated but is used from the best INS. If the INS is not available, attitude is marked as invalid. When the RTS receives new attitude data, it will perform a polynomial fit to the incoming INS data. This fit will be used to extrapolate attitude data and to calculate attitude rate information from the time of the most recent INS attitude data point. By using this fit and utilizing extrapolation algorithms, NAVSSI can guarantee accurate attitude data with relatively low latency. As seen in TABLE-II, attitude latency is critical for many user systems, because the error caused by data latency can quickly exceed the error budget. Therefore, for certain user systems, it is necessary to schedule data output messages to coincide with the receipt of fresh data from the appropriate sensor in order to meet the requirements given in TABLE-II.

The navigation source integration algorithms estimate the accuracy of the data being output by NAVSSI. This accuracy estimate is based on the known nominal error characteristics of the available sensor systems, a comparison of the available data, and the maintenance of long-term sensor accuracy data. Some user systems are sent the accuracy estimation data as part of their data message. For other user systems, these data are used to determine the setting of validity bits.

The NSI algorithms operate automatically or manually. *Position, velocity and attitude each have a hierarchy of* data sources.

A. Automatic Source Selection Mode

Automatic Mode is the default mode. In Automatic Mode, the RTS(s) provide navigation data from the data sources selected by the navigation source integration algorithms to the DCS and external user systems.

B. Manual Source Selection Mode

The operator has the capability to override the automatic source selection algorithms for the data displayed on the DCS and the data sent to external users. The operator is prompted to choose from one or more of the following sources: Position Data, Velocity Data, Attitude Data, and Time Data.

When in manual override mode, the data sent to the DCS, the INS, and the other external users is taken from the manually chosen sources of data. If the operator does not manually choose one or more source(s) for a particular type of data, that data continues to be provided via the NSI algorithms. In addition, the NAVSSI operator is able to manually override the INS integration algorithms and choose the best INS.

If there is a loss of communication with a manually selected source, or if the data from that source is marked as invalid, then the RTS(s) send(s) an alert message to the DCS operator and the following is performed: If position data was manually selected, then the RTS(s) estimate(s) position from the last valid message of the manually selected source and provide(s) this data to the DCS and external users. If velocity data were manually selected, the RTS(s) mark(s) the velocity data being sent to the DCS and external users as invalid. If attitude data was manually selected, the RTS(s) mark(s) the attitude data being sent to the DCS and external users as invalid. If the time source was manually selected, the RTS(s) maintain(s) the last offset calculated from the chosen time source and utilize the microprocessor clock to continue updating time.

V. POSITION DATA REFERENCING

Each RTS resolves navigation position information from each sensor to the same single shipboard reference point known as the Own Ship's Reference Point (OSRP). User systems receive data based upon the integrated OSRP solution, excepting those systems for which the IDS or Interface Design Document (IDD) states that the data shall reflect a specific other data source reference point.

The RTS receives the precise position of a sensor or a user system from the DCS. Position is relative to the *OSRP as follows:*

Distance along the aft axis is referred to as the longitudinal distance. It measures the displacement between the OSRP and the user's system along an axis parallel to the ship's centerline. If the system is physically located behind the OSRP, the distance is positive.

Distance along the Port axis is referred to as the athwartships distance. It measures the displacement between the OSRP and the user's system along an axis parallel to the ship's deck from port to starboard. If the system is physically located left (port side) of OSRP, the distance is positive.

Distance along the Down axis is referred to as the vertical distance. It measures the displacement between the OSRP and the user's system along the vertical axis as defined in the ship's installation drawings. If the system is physically below the OSRP, the distance is positive.

Lever arm data to offset navigation data from each sensor system to OSRP are entered into the RTS system configuration files via the DCS by the installing activity. Once entered, these lever arm data offsets are maintained in non-volatile memory as part of the ship's NAVSSI system configuration, so the RTS can automatically apply the offsets to OSRP. Thus, all user systems receive position data referenced to OSRP, unless the IDS or IDD for that system specifically designated the use of sensor position data without applying the offset to OSRP for that system.

Lever arm data from the following systems (if installed) are provided to the RTS so that they can get their data offset to OSRP: GPS Antennas #1 and #2, and INS #1 and #2.

GPS reset data sent to the ship's INS is referenced to OSRP. This is done in order to make the system work equally well with AN/WRN-6 or the dual GPS Versa Modular European (VME) Receiver Card, a.k.a. GVRC.

If attitude data is not available from the INS, NAVSSI uses the following estimates to complete its OSRP lever arm offsets:

$$\begin{aligned}\text{Heading} &= \text{Tan}^{-1}(V_E/V_N) \text{ for positive } V_E \text{ and } V_N, \\ &= 180^0+\text{Tan}^{-1}(V_E/V_N) \text{ for negative } V_N. \\ &= 360^0+\text{Tan}^{-1}(V_E/V_N) \text{ for negative } V_E \text{ and positive } V_N. \\ \text{Roll} &= 0^0 \\ \text{Pitch} &= 0^0\end{aligned} \tag{1}$$

Where: V_N = Velocity North, and V_E = Velocity East.

VI. INS ACCURACY ESTIMATION

In a typical configuration, NAVSSI communicates with an installed INS. On Block 4.2.1 platforms, this INS is the Ring Laser Gyro Navigator (RLGN) or AN/WSN-7.

Each RTS normally communicates directly with only one INS, but has access to the data from the other INS in a dual RTS/INS installation via a reflective memory link between the two RTSs. In support of the sensor integration algorithms and as an aid to the ship's navigation team, each RTS independently and continuously evaluates the accuracy of both INSs. This independent assessment of INS accuracy utilizes GPS data (when available) and enables NAVSSI to estimate INS accuracy both in terms of absolute accuracy and accuracy relative to other INS. Thus, these routines enable NAVSSI to choose INS data from the more accurate INS. However, the accuracy algorithms will include a minimum ten percent allowance for Hysteresis. This will prevent NAVSSI from repeatedly switching back and forth between the two INSs when both have relatively similar performance characteristics. These accuracy estimation routines are a significant improvement over the Block 2 INS assessment algorithms, which simply utilized the accuracy bits provided by each INS and did not attempt to make an independent assessment of INS accuracy.

The RTS is able to receive and respond to a manual selection of best INS from the DCS.

VII. ESTIMATED POSITION PROCESSING

The RTS calculates Estimated Position (EP) based on discrete position fixes, best available course (or heading as last resort) and speed sources. The RTS is also able to utilize manually entered course and speed to calculated EP. EP data is provided to the source integration algorithms for consideration as a candidate for source integration and to the DCS for display. However, EP is not utilized as source data unless manually selected or as the result of multiple sensor failures.

VIII. RTS OUTPUT DATA

The NAVSSI RTS outputs navigation and time data in a variety of formats. TABLE-II summarizes the data output requirements and lists the interface criticality requirements for maintaining communications in the event of single or multiple points of failure.

TABLE-II: SUMMARY OF BLOCK 4 DATA OUTPUTS

System	Message Rate (Hz) [1]	Position Accuracy (meters)	Attitude Accuracy (msec)	Time Accuracy (msec)
ACDS Block 0	8	100	60	100
KSQ-1	1	100	N/A	1000
SMQ-1C	1 Synchro	16 N/A	10 N/A	10 N/A
SPS-73	Synchro	N/A	N/A	N/A
SQS-53D	1	100	N/A	100
ARC-54	HaveQuick	N/A	N/A	1
TPX-42	8	100	60	100
ADMACS	50	20	10	10
SQQ-89	1	100	N/A	100
WSN-7	1	100	N/A	1
ATWCS/ TTWCS	Almanac	N/A	N/A	N/A
BFTT	1	100	1000	0.1
DMR	1	N/A	N/A	1
GCCS-M	1	100	N/A	1000
CEC	50 [1] 1	20 N/A	10 N/A	100 0.001
CDL-N	8	100	N/A	N/A
IBS	50 [1]	100/20	10/1000	10
ICAN	50 [1]	20/100	10/1000	10
DCS	1	N/A	N/A	N/A
DBB	1	100	1000	1000
DSVL	8	1000	250	125
SCI / Unclass	1	100	1000	100
MK-105 MK-106 ACEG	1	N/A	N/A	0.001
OBC [3]	1	100	N/A	N/A
FODMS (RS-422)	1 50	100 20	N/A 10	N/A 100
RNSSMS	N/A	N/A	N/A	10

System	Message Rate (Hz) [1]	Position Accuracy (meters)	Attitude Accuracy (msec)	Time Accuracy (msec)
IP-1747 WSN-7	0.125 [1]	N/A	N/A	N/A
M-34 MK-160	8 [1]	20	N/A	10
MK-86	1	20	N/A	100
Ship's Network	50 [1]	20	10	10
GAS-1	0.1	N/A	N/A	N/A
LHD8 SubLAN	50 [1]	20	10	10
SLQ-32A	Synchro	N/A	N/A	N/A
SPN-35C	Synchro	N/A	N/A	N/A
SPN-43C	Synchro	N/A	N/A	N/A
SSDS	50 [1] N/A	20 N/A	10 N/A	10 10
SWAN	50 [1]	20	10	10
SPQ-14	Synchro	N/A	N/A	N/A
SPQ-9B	Synchro	N/A	N/A	N/A
SPS-48E	Synchro	N/A	N/A	N/A
SPS-49A	Synchro	N/A	N/A	N/A
SPS-67	Synchro	N/A	N/A	N/A
IFF UPX-29	Synchro 1	N/A 16	N/A 100	N/A N/A
URN-25	Synchro	N/A	N/A	N/A
USC-38	Synchro	N/A	N/A	N/A
USQ-86	N/A	N/A	N/A	TOD
WSC-6	1 Synchro	N/A N/A	N/A N/A	0.001 N/A
OE-XX WSC	Synchro	N/A	N/A	N/A
OE-556 A/U	Synchro	N/A	N/A	N/A
SSR-2A	Synchro	N/A	N/A	N/A
DDRT	0.5	N/A	N/A	N/A
Degauss	Synchro	N/A	N/A	N/A
ABS	50	N/A	N/A	N/A
CIWS	Synchro	N/A	N/A	N/A
RAM MK-31	Synchro	N/A	N/A	N/A
NSSMS MK-57	Synchro	N/A	N/A	N/A
VSTOL OLS MK-11	Synchro	N/A	N/A	N/A
RTS to RTS	50 [1]	N/A	N/A	N/A

1 Data rates are approximate.
2 Multiple messages with highest rate given.
3 "AN/" has been omitted from many system titles in order to accommodate table constraints.

IX. Output Data Time Tagging

Time information within output data messages is accurate to within 200 microseconds (two-sigma) RSS with any timing accuracy of the sensor data when the output message structure provides sufficient resolution to support this accuracy. In the event of a loss of GPS input, NAVSSI is able to maintain time accurate to one millisecond for one day and accurate to ten milliseconds for fourteen days.

X. PRECISE TIME DISTRIBUTION

The NAVSSI RTS provides accurate time to user systems by means of HaveQuick (HQ), Binary Coded Decimal (BCD) time code, Inter-Range Instrumentation Group (IRIG-B) time codes, 1 Pulse Per Second (PPS), and 10 PPS. The HQ, BCD, and 1PPS signals meet the standards specified in ICD-GPS-060. The IRIG-B time conforms to the standards set forth in IRIG Standard 200-98. The 10 PPS signal, implemented in the NAVSSI Precise Time Unit (PTU) has all of the characteristics of the 1 PPS except that it is at 10 times the rate. TABLE-II identifies the accuracy of the time data required by the various user systems. All requirements are in terms of two-sigma level of accuracy.

XI. NAVSSI STANDARD MESSAGE OUTPUT

NAVSSI Navigation Messages (NM) have been created to facilitate future design efforts for use by a wide variety of potential user systems. The NMs' content is independent of the hardware chosen for any particular interface allowing this message to be sent at different rates and over a wide variety of point-to-point and network interfaces. The NM are a generic sub-message format designed to meet the requirements of various navigation user systems, and includes basic PNT data. Other sub-messages include True Wind, Apparent Wind, Magnetic Variation, Own ship distance, and navigation sensor messages.

XII. INFORMATION SECURITY

Initially, NAVSSI was a self-contained system with its subsystems interconnected by an internal LAN, while the RTS connected to the sensors and users via external point-to-point interfaces. This isolated configuration had no Information Security (IS) issues [3], but as the number of interfaces grew to include other networked users, so did the concerns for IS. Two security issues emerged with the LPD-17 class ship when the requirements for NAVSSI included connectivity to a ship's network that may have a path off the ship via Satellite Communications (SATCOM), and the connectivity to both classified and unclassified systems, raising the potential for cross-domain issues [4].

A. Off Ship Connectivity Via SATCOM

The unclassified Ship Wide Area Network (SWAN) on LPD-17 is connected to the Non-classified Internet Protocol Router Network (NIPRNET) via SATCOM, which is protected from the Internet by boundary security measures. However, no security is guaranteed 100%, so the security in depth policy requires that NAVSSI be protected in the event that the Unclassified SWAN security gets breached. The NAVSSI security solution involves both software and hardware.

PNT data is meaningless if it's late, so there is no need to retransmit any lost or otherwise corrupted data, and therefore no need for two-way communications.

This allows NAVSSI to use one-way output Multicast of the NM to the Unclassified SWAN without requiring any incoming feedback. This software solution can be further tightened by a hardware solution using a one-way fiber optic output for absolute security. A passive tap of the output is fed back to the input of the NAVSSI Medium Access Controller (MAC). This fools the MAC into believing the link is up in the absence of periodic data reception indicating connectivity. This combined software and hardware solution ensures the security of NAVSSI against any attempted access from the unclassified SWAN.

B. Potential for Cross-Domain Communications

To complicate matters, the LPD-17 requires that NAVSSI supply the Nav Msgs to the classified SWAN. Of course, a similar one-way fiber solution is used for this interface as well, which ensures that no classified data can leak into NAVSSI. However, as an unclassified system, NAVSSI is providing PNT data to the classified SWAN, which may be used for unintended cross-domain transmissions. While the US Navy permits unclassified PNT data to be fed to a classified system [5], the physical connectivity can potentially be used for other than PNT data.

The risk to the classified SWAN may come from a compromised unclassified system connected to NAVSSI. If the compromised system can gain access to the one-way communications path to the classified SWAN, then it may be able to insert a Trojan horse or other type of malicious code. To prevent any possibility of creating a cross-domain channel through NAVSSI, the interface to the classified SWAN is directly connected to the RTS, where the RTS does not provide any capability of transferring, routing, or any other capability to create a data channel to other interfaces. The RTS is a single image executable program embedded in the subsystem hardware with no means to modify it, or run and other programs or utilities that were not compiled into the installed application. The RTS has no peripheral storage or the ability to allocate memory, so it cannot store any inserted data that is not a valid interface message into its fixed memory structure. The RTS does not have any interactive user capability or command interface that may enable the gain of access. This ensures that no data can be channeled from one interface to another. All data input to the RTS is processed according a to fixed format messages with range bounds on the fixed fields. This data is then used to construct new output data, also in the appropriate fixed output formats, which eliminates any possibility of data being transferred from one interface to another that may create a cross-domain communications channel.

XIII. CONCLUSION

As the pre-eminent secure source of precise, real-time, integrated PNT data for the US Navy surface ships, NAVSSI has demonstrated a tremendous capability to adapt and scale to increasing demands. At the same time, it continues to provide backwards compatibility with legacy systems, allowing them to develop and modernize at their own pace.

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