AEROSPACE INFORMATION REPORT

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Architecture Framework for Unmanned Systems

RATIONALE

The AFUS document is now stabilized. This information is still relevant from a historical perspective as it informed the development of multiple SAE AS-4 JAUS Service Sets. However, it is no longer actively being updated.

STABILIZED NOTICE

This document has been declared "STABILIZED" by SAE AS-4JAUS Joint Architecture for Unmanned Systems Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

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1. SCOPE

This SAE Aerospace Information Report (AIR) describes the Architecture Framework for Unmanned Systems (AFUS). AFUS comprises a Conceptual View, a Capabilities View, and an Interoperability View. The Conceptual View provides definitions and background for key terms and concepts used in the unmanned systems domain. The Capabilities View uses terms and concepts from the Conceptual View to describe capabilities of unmanned systems and of other entities in the unmanned systems domain. The Interoperability View provides guidance on how to design and develop systems in a way that supports interoperability.

1.1 Purpose

The purpose of this Aerospace Information Report is to communicate to the unmanned systems community a common set of principles, terms, concepts, patterns, structures, and guidance for creating system architectures that include or interact with unmanned systems.

1.2 Overview

The approach of the Unmanned Systems Committee to the generation of the Architecture Framework for Unmanned Systems has evolved over the history of the Framework. From initially approaching the Framework with the intent to identify individual capabilities, needed immediately, the committee now approaches the Framework with the intent of addressing the Unmanned System as a whole. As Unmanned Systems gain acceptance, the focus of the Framework has moved from individual systems to systems of systems. Finally, as the abilities of Unmanned Systems grow, it has been necessary to ensure that the capabilities described herein are supportive of more autonomous systems, while still enabling the teleoperated systems.

Autonomy is an emergent property of this Framework. For an unmanned system to be autonomous, it takes multiple characteristics of this Framework for the system to be somewhat self-aware and to complete its task/mission without human intervention. Autonomy is key and critical to the future of unmanned systems as end users desire systems that permit them to perform other tasks while still making the major decisions of the task/mission. There is a need for a single operator (human) to control multiple unmanned systems. For example in port security, multiple ground and surface vehicles may work together monitoring a port or ship, only needing a single security person to make the final decision as to what action to take when a security anomaly is detected.

Expanding markets for unmanned systems are demanding increased autonomy characteristics. The AS-4 committee recognizes this fact and continues to include the necessary characteristics in this Architecture Framework.

1.3 Field of Application

Fields of application of AFUS include unmanned systems of all classes, command and control (C2) systems, and related areas such as communications, safety, security, sensors, manipulators, and simulation.

1.4 How to Use

This Architecture Framework has several uses:

- to provide background information on unmanned systems to a variety of readers;
- to provide a common vocabulary for understanding standards, specifications, and designs for unmanned systems;
- to provide a common set of semantics for the vocabulary;
- to provide a base set of behaviors common in unmanned systems;
- to provide guidelines for developing systems that are interoperable; and
- to provide a set of capabilities from which unmanned systems requirements can be derived.

AFUS is intended to serve as a companion document to other Specifications published by AS-4. As such, it gives additional and supporting information to system procurers and specifiers, designers, program managers, standards writers, and other readers that require a more thorough understanding of the Specifications.

1.5 Acknowledgements

Development of this report was supported in part by U.S. Army Aviation and Missile Research, Development, and Engineering Center contract W31P4Q-05-A-0031/0008.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS4893 Generic Open Architecture (GOA) Framework

AIR5645 JAUS Transport Considerations

AS5669 JAUS/SDP Transport Specification

AS5684 JAUS Service Interface Definition Language

AS5710 JAUS Core Service Set

AS6009 JAUS Mobility Service Set

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

E 2521 - 07a Standard Terminology for Urban Search and Rescue Robotic Operations

F2541-06 Standard Guide for Unmanned Undersea Vehicles (UUV) Autonomy and Control

F 2395 - 05 Standard Terminology for Unmanned Air Vehicle Systems

2.1.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

FAA Form 7233-1 Flight Plan, http://forms.faa.gov/forms/faa7233-1.pdf.

2.1.4 IEEE Publications

Available from Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854-1331, Tel: 732-981-0060, www.ieee.org.

IEEE-Std-1471-2000 Recommended Practice for Architectural Description of Software-Intensive Systems

2.1.5 ISO Publications

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

[OSI] ISO/IEC 7498-1:1994Open Systems Interconnection - Basic Reference Model: The Basic Model

2.1.6 NASA Publications

Available from NASA, Documentation, Marshall Space Flight Center, AL 35812, www.nas.nasa.gov.

[NASA-PSD] Planetary Science Data Dictionary, JPL D-7116 Rev. E, Jet Propulsion Laboratory, California Institute of Technology. 2002

2.1.7 NIST Publications

Available from National Institute of Standards and Technology, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

[NIST-ALFUS] Huang, Hui-Min, ed. Autonomy Levels for Unmanned Systems (ALFUS) Framework, Volume I: Terminology, Version 1.1. National Institute of Standards and Technology Special Publication 1011, Sept. 2004

[NIST-SI] Taylor, Barry N., ed. Guide for the Use of the International System of Units (SI). National Institute of Standards and Technology Special Publication 811, 2008 Edition. 2008

2.1.8 U.S. Government Publications

Available from
http://www.ndia.org/Divisions/Divisions/Robotics/Documents/Content/ContentGroups/Divisions1/Robotics/UMS_SafetyPolicyVer096_Released.pdf

UNMANNED SYSTEMS SAFETY GUIDE FOR DOD ACQUISITION, 27 June 07

2.1.9 W3C Publications

Available from the World Wide Web Consortium, MIT, 32 Vassar Street, Room 32-G515, Cambridge, MA 02139 USA, Tel: 617-253-2613, www.w3.org.

[W3C04] W3C Technical Architecture Group. Architecture of the World Wide Web, Volume One. W3C Recommendation, December 2004. http://www.w3.org/TR/2004/REC-webarch-20041215/.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

[ALBUS] Albus, James S. and Alexander M. Meystel, Engineering of Mind: An Introduction to the Science of Intelligent Systems, John Wiley & Sons, 2001.

[MEYSTEL] Meystel, Alexander M. and James S. Albus, Intelligent Systems: Architecture, Design, and Control. New York: John Wiley & Sons, 2002.

[DICT07] Dictionary.com Unabridged (v 1.1). Random House, Inc. 02 Jan. 2007.

[HALPERN95] Halpern, J. Y., Ronald Fagin, et al., Reasoning about Knowledge, MIT Press, 1995.

[HALPERN03] Halpern, J. Y., Reasoning about Uncertainty, MIT Press, 2003.

[HAM] Hamilton, J.A, Jr. Modeling Command and Control Interoperability: Cutting the Gordian Knot. SCS Press, 2004.

[KELSO94] Kelso, T. S., Computers & Satellites column, Satellite Times. 1994-1998. http://celestrak.com/columns/.

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[MILLER03M] Miller, Mark S., Ka Ping Yee, and Jonathan Shapiro. Capability myths demolished. Technical report, Combex, Inc., 2003.

[MILLER03P] Miller, M. S. and J. S. Shapiro. Paradigm regained: Abstraction mechanism for access control. In Asian Computing Conference, Dec. 2003.

[NELSON01] Nelson, R. A., et al. The Leap Second: Its History and Possible Future. 2001 Metrologia 38 509-529.

[WORDNET] WordNet 3.0, Princeton University, 2006.

[SMITH02] Smith, Richard E. Authentication. Addison Wesley. 2002.

2.3 Definitions

ACCELERATION: The second derivative of pose with respect to time, referred to as pose-dot2.

ACCESS: Permission to learn about the existence of an entity and some or all of the states and attributes of the entity.

ACOUSTIC: Observing acoustic energy, possibly discerning direction, strength, and nature of audio signals.

ACTUATOR: A motor or mechanism capable of controlled prismatic (linear) or revolute (angular) motion.

ADDRESS: A unique identifier that allows a transport to distinguish between accessible entities.

AGENT: An entity that can act on behalf of another entity.

ALTITUDE: The distance above a reference surface measured normal to that surface. Altitudes should not be measured along extended body radii, but along the direction normal to the geoid; these are the same only if the body is spherical. Common surface references include Mean Sea Level (MSL), above ground level (AGL), and above sea floor (ASF). See also: ELEVATION, HEIGHT, DEPTH.

AMBIENT AUTHORITY: A property of an authority scheme where merely possessing an authority is sufficient, explicit selection is not necessary.

ANGLE: A measure of the geometric figure formed by the intersection of two lines or planes. Structures containing the word 'angle' should include origin and relevant sign conventions where applicable.

AREA: The lines that make up its boundary. In a raster world model, it is represented as a collection of grid cells. In a vector world model, it is represented as a collection of lines.

AUTHENTICATION SCHEME: Processes and mechanisms used to establish an entity's identity as genuine, usually by means of exchange of credentials.

AUTHORITY SCHEME: A mechanism to grant, revoke, and evaluate the authorities of an entity.

AUTHORITY: A mechanism to assure an entity that another has permission to access or control, often involving credentials.

AUTHORIZATION: The delegating, granting or revoking of rights to a principal.

AUTONOMY: The condition or quality of being self-governing. [NIST-ALFUS]

AXIS SYSTEM: The set of (usually three orthogonal, right-handed) axes of a coordinate system. All axis systems must be orthogonal.

AXIS OF SYMETRY: A straight line with respect to which a body or figure is symmetrical.

AZIMUTH: One of two angular measures in a spherical coordinates system. Azimuth is measured in a plane which is normal to the principal axis, with increasing azimuth following the right hand rule convention relative to the positive direction of the principal axis. [NASA-PSD] adopts the convention that an azimuth angle is never signed negative. The point of zero azimuth must be defined in each case.

BALLISTIC: Relating to or characteristic of the motion of objects moving under their own momentum and the force of gravity. [WORDNET]

BASE: A measure to be added to a value. [NASA-PSD]

BATHYMETRY: The measurement of the depths of oceans, seas, or other large bodies of water; or the data derived from such measurement, esp. as compiled in a topographic map. [DICT07]

BATTERY: A source of electrical energy.

BAY: A compartment.

CHARACTERISTIC: A prominent attribute or aspect of something; a distinguishing quality [WORDNET]

CLEARANCE LEVEL: A measure of the trustworthiness of a principal. [MILLER03P]

COLLABORATION: The process by which multiple systems jointly work together by sharing data, such as their coordinates or their maneuver(s), or by acquiring intelligence to perform a mission synergistically (i.e., perform better than each could have alone).

COMPONENT: (1) The part of a vector associated with one coordinate. (2) A constituent part. [NASA-PSD]

CONSTANT: A value that does not change significantly with time. [NASA-PSD]

CONSUMPTION: The usage of a consumable. [NASA-PSD]

CONTRAST: The degree of difference between things having a comparable nature. [NASA-PSD]

CONTROL: Permission to access an entity and alter some or all of its state.

COORDINATE SYSTEM: Defined by an origin, axes system, position system, and rotation system.

COORDINATION: The ability for unmanned systems to work together harmoniously through collaboration data such as mission or task plans, coordinates of maneuver(s); a common way is for a superior to coordinate the task execution of the subordinates to accomplish the missions.

CORRELATION: (1) Mutual relation of two or more things, parts, etc. [DICT07]

COUNT: A numeric value indicating a current total or tally. The word count is implied by the use of plural descriptor words such as lines, bytes, or bits. [NASA-PSD]

CREDENTIALS: A unique set of encoded data assigned to an entity that allows the entity to authenticate itself (with help of an issuing entity) to other entities. The entity's name is usually encoded in its credentials.

DEPTH: The distance below a reference surface measured normal to that surface. The reference surface is usually actual sea level for use by undersea vehicles. See ALTITUDE.

DESCRIPTION: A free-form character string that provides a description of the item identified. [NASA-PSD]

DESIGNATOR: A representation of a resource's existence and how to access it.

DEVIATION: Degree of deviance. [NASA-PSD]

DISCOVERY: The mechanism of learning the existence of entities on one or more communication segments.

DISCRETIONARY: A property of an authority scheme that allows a principal to grant authority that it possesses to some other principal.

DISTANCE: A measure of the linear separation of two points, lines, or surfaces. See also ALTITUDE, DEPTH, which refer to specific types of distance. The use of the word 'distance' supersedes the use of the word RANGE as a measure of linear separation. See also: RANGE.

DURATION: An amount of time, not associated with any points on a time scale. [NASA-PSD] defines duration as "a measure of the time during which a condition exists."

EJECT: To throw off or cause to be detached.

ELECTROMAGNETIC: Observation of heat (IR), light, radio frequency radiation, and magnetic fields.

ELEVATION: (1) The distance above a reference surface measured normal to that surface. Elevation is the altitude of a point on the physical surface of a body measured above the reference surface; height is the distance between the top and bottom of an entity. See also: ALTITUDE. (2) An angular measure in a spherical coordinate system, measured positively and negatively on a great circle normal to the azimuthal reference plane. The zero elevation point lies in the azimuthal reference plane, and positive elevation is measured towards the direction of the positive principal axis. See also: AZIMUTH.

EMISSION: Act of sending something out into air or space.

EMITTER: Device capable of emitting.

END EFFECTOR: The last link of a manipulator, often modular to accept various tools or instruments.

ENERGY CONVERSION: The transformation of energy of one type to energy of another type.

ENERGY SOURCE: A physical mechanism that produces power for a platform, often consuming fuel in the process.

ENGINE: A device for converting thermal energy into mechanical energy or power to produce force and motion. [DICT07]

ENTITY: A discrete object possessing an identity. Entities usually have self-contained communications and computation resources. An entity is unique within a domain.

ENVELOPE: A set of propulsion, pose, and kinematic limits within which mobility is considered safe to a platform.

ENVIRONMENT MOTION: The relative motion of the environment that affects the motion of the platform.

ENVIRONMENT: Generic, natural conditions; e.g., weather, climate, ocean conditions, terrain, vegetation; modified environment can refer to specific induced environments; e.g., dirty battlefield environment, nuclear/chemical/biological environment, etc. Environment includes those conditions observed by the system during operational use, standby, maintenance, transportation, and storage.

EPOCH: A reference against which the occurrences of the scale interval can be measured, often given as a time tag. [NASA-PSD] defines epoch as "a specific instance of time selected as a point of reference."

ERROR: The difference between an observed or calculated value and a true value. [NASA-PSD]

EVENT: An occurrence at a specific location and point in time, past or future.

EXISTENCE: Knowledge of a resource and how to access it.

EXCLUSION ZONE: A 2D or 3D region, often represented as an *n*-sided polygon, that specifically bounds the allowed region of a mobility platform such that the platform is not allowed to travel inside the defined area. An exclusion zone may be specified inside of an Operating Zone; e.g., an island lies in the center of the operating zone.

EXPECTATION: The degree of probability that something will occur. [DICT07]

EXTENTS: The set of height, width, and length measures of a given space; the three-dimensional bounding box of a given space.

FACTOR: A measure by which another measure is multiplied or divided. [NASA-PSD]

FEATURE CLASS: A classification assigned to geographic features; a means of differentiating types of data within a world model knowledge store.

FIRST: An indication of the initial element in a set or sequence. As with minimum and maximum, the values in the set may be out of order or discontinuous. [NASA-PSD]

FORMAT: A specified or predetermined arrangement of data within a file or on a storage medium. [NASA-PSD]

FRACTION: The non-integral part of a real number. See also: BASE. [NASA-PSD]

FREQUENCY: Tate of occurrence of past and/or future time tags; the number of cycles completed by a periodic function in unit time. [NASA-PSD]

FUEL: Stored energy.

FUEL CAPACITY: The amount of fuel that can be stored.

GEOREFERENCED INFORMATION: The coordinates of the origin of an object with respect to a world coordinate system.

GOAL: A result or state to be achieved or maintained.

GRANT: To give or delegate a right to a principal.

GRID EXTENT: The number of rows and columns of the grid.

GRID RESOLUTION: The size of each grid cell.

HARDPOINT: A location on a platform that is capable of carrying external stores.

HAZARD: Any object, environmental characteristic, internal function, or internal hardware and software component that has the potential to interfere with the proper functioning of the unmanned system, or that degrades the probability of success of the system's goal.

HOST PLATFORM: A manned or unmanned platform from which a remote system may be launched or recovered.

HEIGHT: The vertical distance between a point and a reference datum.

HYDROGRAPHY: The science of the measurement, description, and mapping of the surface waters of the earth, with special reference to their use for navigation. [DICT07]. See also: BATHYMETRY.

IDENTITY: A set of distinguishing characteristics of an entity that makes it distinct from other entities. Identity must be unique within a domain.

INDEX: An indicator of position within an arrangement of items. [NASA-PSD]

INTERVAL: A duration starting at a time tag, marking a finite continuous range on a time scale. [NASA-PSD] has two definitions; AFUS uses "1) The intervening time between events."

JERK: The third derivative of pose with respect to time, referred to as pose-dot3.

JETTISON: See EJECT.

JOINT: A point of articulation between two or more parts of a body[1].

KINEMATIC LIMITS: The minimum and maximum motion allowed for a body. For instance, a body may require very low jerk to avoid damage to internal equipment.

KINEMATICS: The branch of mechanics that deals with pure motion, without reference to the masses or forces involved in it [DICT07].

KINETICS: The branch of mechanics that deals with the actions of forces in producing or changing the motion of masses [DICT07].

LAST: An indication of the final element in a set or sequence. As with minimum and maximum, the values in the set may be out of order or discontinuous. [NASA-PSD]

LENGTH: A measured distance or dimension. See also: HEIGHT, WIDTH.

LEVEL: The magnitude of a continuously varying measure. [NASA-PSD]

LINE OF BEARING: The vector from vehicle to current destination.

LINE: An ordered list of coordinate pairs defining the points through which the line is drawn. In a raster world model, it is represented as a collection of grid cells. In a vector world model, it is represented as a collection of points.

LINEAR ACTUATOR: An actuator with range of motion in a straight line.

LINK: A rigid body between joints.

LOCALIZATION: The capability of an entity to determine its Pose in a specific Coordinate System.

[1] Excerpted from *The American Heritage Dictionary of the English Language, Third Edition* Copyright © 1992 by Houghton Mifflin Company. Electronic version licensed from Lernout & Hauspie Speech Products N.V., further reproduction and distribution restricted in accordance with the Copyright Law of the United States. All rights reserved.

LOCATION: The position or site of an entity.

LONGITUDE: In a cylindrical coordinate system, the angular distance from a standard origin line, measured in the plane orthogonal to the axis of symmetry.

MANIPULATOR: A chain of links connected with actuators at the joints and having one or more end effector.

MAP: A description of the topology in an area of interest. The purpose of a map is to define the domain in which a system is expected to perform. Examples include a map of waypoints, poses of a manipulator, or the location of pallets in a warehouse.

MASK: An unsigned numeric value representing the bit positions within a value. [NASA-PSD]

MASS-BALANCE: The mass and moments of inertia of a body.

MAXIMUM: An indicator of the element in a range that has the greatest value, regardless of the order in which the values are listed or stored. For example, in the set {4, 5, 2, 7, 9, 3}, the minimum is 2, the maximum is 9. The use of minimum and maximum, as with first and last implies that the set may be out of order or discontinuous. [NASA-PSD]

MEASURE: A single observed value of a certain quantity; includes name, quantity, unit, and value. For example: engine coolant (name) temperature (quantity) in degrees kelvin (unit). [NASA-PSD]

MEASUREMENT: The capture of data with a customary unit. [NASA-PSD]

MEDIA: The physical substance through which communication signals are transmitted.

MINIMUM: An indicator of the element in a range that has the least value, regardless of the order in which the values are listed or stored. See MAXIMUM for an example. [NASA-PSD]

MISHAP RISK ACCEPTANCE LEVEL: The level at which the occurrence of a mishap event is acceptable based on the relationship between mishap occurrence frequency and severity, given the effect of the mishap event on the overall system’s function and/or replacement.

MISHAP RISK: See RISK.

MISHAP: An occurrence of interruption from normal functioning caused by the encounter of a hazard.

MISSION: A set of goals, with constraints, assigned to the unmanned system(s).

MISSION BEHAVIOR: A set of actions taken based on environmental and mission parameters. Examples include hug the treeline, maintain vehicle separation distances, or follow littoral navigation rules.

MOBILITY: The capability of an unmanned system to move from place to place, with its own power and while under any mode or method of control.

MODULATION: The act of causing the amplitude, frequency, phase, or intensity of (a carrier wave) to vary in accordance with a sound wave or other signal, the frequency of the signal wave usually being very much lower than that of the carrier. [DICT07]

MOTION: The rates of change (derivatives) of a pose with respect to time: velocity, acceleration, and jerk.

NAME: A (usually) human-readable identifier for an entity. Names are (usually) unique within a domain.

NOTE: A textual expression of opinion, an observation, or a criticism; a remark. [NASA-PSD]

NUCLEAR/BIOLOGICAL/CHEMICAL: Observation of the existence of certain chemical compounds, biological agents, or radioactive substances, possibly discerning plumes.

OBSERVATION: To collect information by measurement of the environment via sensors that produce signals that can be analyzed.

ONTOLOGY: A rigorous and exhaustive organization of some knowledge domain that is usually hierarchical and contains all the relevant entities and their relations. [WORDNET]

OPERATING ZONE: A 2D or 3D region, often represented as an *n*-sided polygon, that specifically bounds the allowed region of a mobility platform such that the platform is not allowed to travel outside the defined area.

OPERATOR CONTROL UNIT: A hardware and/or software interface that allows a human to command or monitor one or more unmanned systems.

ORIGIN: The position and orientation context of the coordinate system.

PAN TILT UNIT: A manipulator with two orthogonal revolute actuators.

PARAMETER: A variable. [NASA-PSD]

PAYLOAD: A device carried by a vehicle, usually in a bay or attached to a hardpoint.

PERCENTAGE: A part of a whole, expressed in hundredths. [NASA-PSD]

PERCEPTION: An unmanned system's capability of sensing and building an internal model of the environment within which it is operating, and classifying entities, events, and situations perceived in the environment. [NIST-ALFUS]

PERIOD: The duration of a single repetition of a cyclic phenomenon or motion. [NASA-PSD]

PLANNING: The process to generate tactical goals, a route (general or specific), commanding structure, coordination, and timing for one or more unmanned system. Plans can be generated either in advance by operators on an OCU or in real-time by the onboard, distributed software systems.

PLATFORM: The physical infrastructure of an entity.

PLATFORM GEOMETRY: The physical configuration of a platform contributing to its mobility characteristics.

POINT: A single group of coordinate values. A point normally represents a geographic feature that is too small to be represented as a line or area. In a raster world model, it is represented as a single grid cell. In a vector world model, it is represented as a single group of coordinates.

POINTMAN: A human (soldier in the military domain) assigned some distance ahead of a patrol to set pace and direction, and serve as a lookout. The capability of an unmanned system to perform tasks analogous to a soldier pointman.

POSE: The position and orientation of an entity measured in a known coordinate system, typically representing all six possible degrees of freedom, but sometimes limited to x, y, and heading in surface- or ground-based systems.

POSITION SYSTEM: The three measures of a three dimensional position. All position systems must be right-handed.

POWER PLANT: A mechanism that converts energy into propulsive power. Internal combustion engines, electric motors, and nuclear reactors are examples of power plants.

PRINCIPAL: An entity and its collection of authority.

PRINCIPLE OF LEAST AUTHORITY: Only enough authority should be granted to a principal for it to fulfill its assigned responsibilities.

PROPERTY: A property of an authority scheme that allows principles write access only to those resources classified at or above their clearance level. [MILLER03P]

PROPRIOCEPTIVE: The ability of an entity to sense or observe changes in its own position, orientation and motion in space.

PROPULSION EFFECTOR: A mechanism that converts propulsive power in to platform motion. Tires, tracks, propellers, screws, jet exhaust, legs, and feet are examples of power transfer mechanisms.

PROPULSION: The mechanism by which a platform is mobile. Propulsion is produced by a system of power plants, transmissions, and propulsion effectors.

PYLON: An extension of a hardpoint.

QUANTITY: One of a set of quantities for which a standard (base or derived) unit is defined in [SI] and [NIST08]. [NASA-PSD]

RANGE: Numeric values which identify the starting and stopping points of an interval. [NASA-PSD]

RATE: The amount of change of a measure per unit time. [NASA-PSD]

RATIO: The relation between two measures with respect to the number of times the first contains the second. [NASA-PSD]

REALM: A physical or logical space in which all entities of interest are unique.

RECOGNITION: The identification of something as having been previously seen, heard, known, etc. [DICT07]

REMOTE CONTROL: A mode of operation of an unmanned system wherein the human operator, without benefit of video or other sensory feedback, directly controls the actuators of the unmanned system on a continuous basis, from off the vehicle and via a tethered or radio linked control device using visual line-of-sight cues.

REMOTELY GUIDED: An unmanned system requiring continuous input for mission performance is considered remotely guided. The control input may originate from any source outside of the unmanned system itself. This mode includes remote control and tele-operation.

RESOLUTION: A quantitative measure of the ability to distinguish separate values. [NASA-PSD]

RESOURCE: An entity that requires knowledge of existence and granting of certain rights to access.

REVOKE: To take away a right from a principal.

REVOLUTE ACTUATOR: An actuator with range of motion in an arc.

RISK MANAGEMENT: General design processes to reduce the mishap occurrence probability and/or severity.

RISK: The relationship of a mishap occurrence probability and severity

ROTATION SYSTEM: The three measures of a three dimensional rotation. All rotation systems must be right-handed.

ROUTE: A specification of the transitions between elements in a map. Routes can be used to describe the possible "legal" transitions between map elements (possibly including constraints on those transitions), and also to indicate the choices of state transitions selected to fulfill a mission.

SAFETY: Freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment. [MILSTD882D]

SCALE INTERVAL: An observable, repeatable phenomenon obeying a definite law, such as Earth's rotation or the resonance of a Cesium-133 atom.

SCOUT: Also referred to as unmanned scout or robotic scout: a person, aircraft, or ship sent out to obtain information, esp. in preparation for military action; the capability of an unmanned system to perform tasks analogous to a human scout.

SEGMENT: The physical or logical subdivision or aggregation of communication media. Segments may be individually addressed.

SEISMIC: Pertaining to shock waves propagating through a planetary crust.

SENSOR FUSION: A process in which data, generated by multiple sensory sources, are correlated to create information and knowledge. Sensor information, when fused, may yield immediately actionable combat information and/or intelligence. The capabilities are of four essential types: Detection, Classification, Recognition, and Identification.

SENSOR PRODUCT: The data output of a sensor; also the higher order result of various sensor processing steps.

SENSOR: Equipment that detects, measures, and/or records physical phenomena, and indicates objects and activities by means of energy or particles emitted, reflected, or modified by the objects and activities.

SENSORY PROCESSING: Computing processes that operate on either direct sensor signals or on low-level sensory signatures to detect, measure, and classify entities and events and derive useful information, at proper resolutions and at levels of abstractions, about the world. Sensory processes can be organized hierarchically with proper relative spatial and temporal resolutions and organized horizontally with assigned but coordinated focuses.

SEQUENCE: (1) An arrangement of items in accordance with some criterion that defines their spacewise or timewise succession; (2) An orderly progression of items or operations in accordance with some rule, such as alphabetical or numerical order. [NASA-PSD]

SET: A collection of items having some feature in common or which bear a certain relation to one another. [NASA-PSD]

SIGNAL: A discernable state or change of state in a communication medium that conveys information. A signal may be a single bit or an entire message.

SLEW: See SLUE.

SLUE: To turn about; swing around. [DICT07]

SPEED: A directionless measure of time rate of motion, usually taken as the magnitude of the velocity vector. Speed may be relative to a fixed or moving medium; e.g., ground speed versus air speed.

START: An indication of the beginning of an activity or observation. [NASA-PSD]

STATION KEEPING (and maybe LOITER too): TBD after resolving my question/comment in 5.6.3

STOP: An indication of the end of an activity or observation. [NASA-PSD]

TACTICAL BEHAVIOR: See MISSION BEHAVIOR

TACTILE: Observing objects that physically contact the unmanned system.

TASK: A named activity performed to achieve or maintain a goal. Mission plans are typically represented with tasks. Task performance may, further, result in subtasking. Tasks may be assigned to operational units via task commands.

TEAM: A collection of entities for a particular task or subtask.

TEAM OF TEAMS OR SYSTEM OF SYSTEMS: Grouping(s) of teams for a particular mission.

TEAMING: The linking together of platforms, forces, or systems to complete a mission or task collectively that would be more difficult to do if the units acted separately. The process is characterized by distributed operations and high tempo maneuvers, which demands rapid synchronization, swift adaptation of plans and control measures, flexible groupings of distributed staff elements, and direct exchanges between commanders across hierarchies. For example, manned and unmanned platforms can be teamed to emphasize their complementary strengths. The unmanned systems have the further requirements of being able to easily and quickly communicate their intentions, goals, present state in the accomplishment of these goals, intended next action, and current problem areas. Additionally, they have to be able to be re-tasked easily to participate in the current overall goal and to fit into their new position in the organizational structure.

TELE-OPERATION: A mode of operation of an unmanned system wherein the human operator, using video feedback and/or other sensory feedback, either directly controls the actuators or assigns incremental goals, waypoints in mobility situations, on a continuous basis, from off the vehicle and via a tethered or radio linked control device. In this mode, the unmanned system may take limited initiative in reaching the assigned incremental goals. [NIST-ALFUS]

THIRD PARTY CONTROL: Control of one or more of an unmanned system’s payloads, sensors, or other capabilities by someone other than the unmanned system’s controller.

TIME SCALE: The combination of the rate at which time passes (scale interval) and one or more points in time (epoch).

TIME TAG: An infinitesimal instant in time, marking a point on a time scale.

TRANSMISSION: A mechanism that multiplies propulsive power by a (possibly variable) factor.

TRANSPORT: A mechanism for communication that defines an addressing scheme and message encoding scheme. Transports are often tunneled through other transports.

UNIT: A determinate quantity adopted as a standard of measurement. [NASA-PSD]

VELOCITY: The first derivative of pose with respect to time, referred to as pose-dot. See also: SPEED.

VISUAL: Electromagnetic sensing limited to visible and near-visible light.

WAVEFORM: The shape of a wave, a graph obtained by plotting the instantaneous values of a periodic quantity against the time. [DICT07]

WAYPOINT: A destination that an unmanned systems is directed to reach, within a given tolerance.

WIDTH: The distance between two sides of an entity. See also: HEIGHT, LENGTH.

WORLD MODEL: An unmanned system’s internal representation of the world. The world model may include models of portions of the environment, as well as models of objects and agents, and a system model that includes the intelligent unmanned system itself.

2.4 Acronyms

AFUS: Architecture Framework for Unmanned Systems

AIR: Aerospace Information Report

ALFUS: Autonomy Levels for Unmanned Systems

AS: Aerospace Standard

AUS: Autonomous Underwater System

C2: Command and Control

DAPS: Document Automation and Production Service

DOD: Department Of Defense

DOF: Degrees Of Freedom

DUT1: Difference Between UTC and UT1

ELT: Emergency Locator Transponder

EOD: Explosive Ordnance Disposal

ERA: Earth Rotation Angle

FAA: Federal Aviation Administration

GIS: Geographic Information System

GMT: Greenwich Mean Time

GOA: Generic Open Architecture

GPS: Global Positioning System

HMI: Human Machine Interface (see also OCU)

IDD: Interface Definition Document

IED: Improvised Explosive Device

IEEE: Institute of Electrical and Electronics Engineers

IR: InfraRed light

ISO: International Organization for Standardization

JAUS: Joint Architecture for Unmanned Systems

JPL: Jet Propulsion Laboratory

LADAR: LAser Detection And Ranging

LASER: Light Amplification by Stimulated Emission of Radiation

NASA: National Aeronautics and Space Administration

NBC: Nuclear-Biological-Chemical

NED: North-East-Down

NIST: National Institute for Standards and Technology

OCU: Operator Control Unit

PKI: Public Key Infrastructure

POLA: Principle Of Least Authority

PSDD: Planetary Science Data Dictionary

PTU: Pan-Tilt Unit

RF: Radio Frequency

SI: International System of Units

TAI: International Atomic Time

TT: Terrestrial Time

UAS: Unmanned Aircraft System

UAV: Unmanned Air Vehicle

UGV: Unmanned Ground Vehicle

UML: Unified Modeling Language

UMS: Unmanned System

UMV: Unmanned Maritime Vehicle

USV: Unmanned Surface Vehicle

UT1: Universal Time corrected for polar motion

UT: Universal Time

UTC: Universal Coordinated Time

UUV: Unmanned Underwater Vehicle

UV: Ultraviolet Light

UXO: Unexploded Ordnance

VIN: Vehicle Identification Number

WGS: World Geodetic System

3. ARCHITECTURE FRAMEWORK FOR UNMANNED SYSTEMS

The domain of unmanned systems started with individual robots controlled by radio-control or tele-operation and grew to networked groups of systems (of various levels of autonomy) controlled by C2 centers. The Architecture Framework for Unmanned Systems (AFUS) can be used to build architectures for any conceivable system (or system of systems) on the continuum between these two extremes.

3.1 Architecture of the Framework

An architecture framework is a structure that supports the organization and development of architectures for systems. This architecture framework provides the objectives, rules and infrastructure for the creation and use of system architectures. The objectives are the high-level attributes to be supported and are described in 3.2. The rules are in the form of architectural principles, given in 3.3, which are to be followed to ensure the architecture framework exhibits certain quality attributes. The infrastructure is described by a number of architectural views with prescribed types of information and features as described in 3.4.

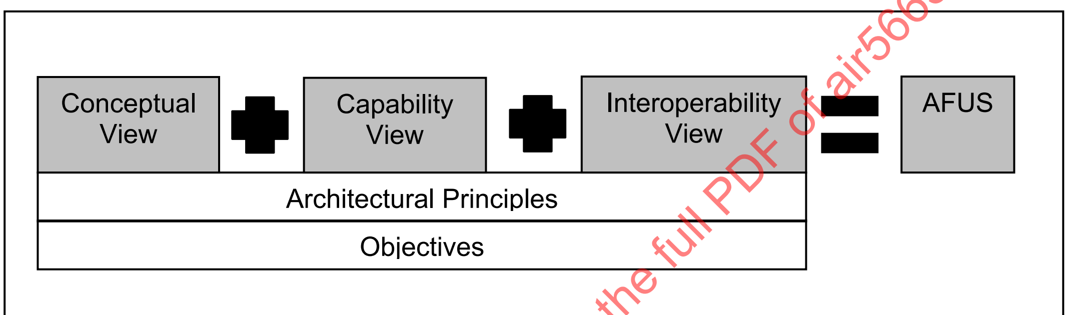

FIGURE 1 - ARCHITECTURE OF THE FRAMEWORK

The AFUS is divided into three views: one describing *concepts,* one describing *capabilities,* and one describing *interoperability*. The Conceptual View defines terms and concepts common in unmanned systems. This provides a consistent vocabulary used throughout the AS-4 document set. The Capability View lists the possible abilities and behaviors of unmanned systems using terms defined in the Conceptual View. The Interoperability View discusses the various aspects of interoperability across unmanned systems. FIGURE 1 demonstrates how these complimentary views, subjected to consistent architectural principles and objectives, represent the core of AFUS.

3.2 Objectives

The Architecture Framework is intended to support the following objectives:

- Support for all classes of unmanned systems,
- interoperable operator control units,
- interchangeable/interoperable payloads,
- and interoperable unmanned systems.

3.3 Architectural Principles

An architectural principle is a fundamental rule that applies to a large number of situations and variables. [W3C04] An architecture simplifies the process of creating system designs by making decisions in advance about characteristics of all systems designed for that architecture. An architect must follow certain principles when making those decisions so they result in a consistent, coherent, and ultimately usable architecture. Similarly, an architecture framework simplifies the process of creating system architectures. The principles used in creating AFUS are described in the following sections.

3.3.1 Clear Semantics

Clear semantics means that it is clear from the representation what semantics are intended. For example, when representing a time, the full semantics will include which time scale was used to obtain the time.

3.3.2 Orthogonality and Separation of Concerns

Orthogonality is the concept that two or more things will undergo changes independent of one another.

Separation of Concerns is the process of decomposition that isolates things to reduce coupling between things that are otherwise unrelated. For example, a controller has to authenticate in order to obtain a position report from a robot, so the concerns of representing position and authentication should be separated to avoid coupling the representations of authentication and position.

Another notable example of Separation of Concerns is separation of policy and mechanism. It is essential that a policy (e.g., which entities are allowed to get position reports) and the mechanism to enforce it are not inextricably linked. This separation will allow changes to policy and mechanism independently without requiring changes to the other. Policy and mechanism are orthogonal to one another.

3.3.3 Technology Independence

The unmanned systems domain will evolve for many years. Depending on or favoring a specific technology may prevent the community from taking advantage of technological advances that will change the way that problems can be solved. If a technology is essential for solving a problem today, the capability it provides should be abstracted out and the solution described in terms of the capability, not directly on the technology itself.

3.3.4 Platform Independence

A similar problem exists concerning types of unmanned system platforms. Several standards have been developed with a specific type of platform in mind, such as UGVs or UAVs. This Framework must not favor one platform over others. Some unmanned systems are not physical (e.g., simulators). Some are not mobile. For those that are mobile, their form of locomotion might be lighter-than-air, articulated legs, a single ball, snake-like segments, or any other form imaginable by researchers.

3.3.5 Mission Independence/Isolation

There should be no assumed mission or restriction on types of mission that an unmanned system can carry out. It should not be assumed that there will be a certain number or type of unmanned systems or C2 systems assigned to a mission.

3.3.6 Compute Capability Independence

There should be no assumption about the number or types of compute capabilities available to an unmanned system. Even far into the future, there will be unmanned systems with minimal compute capabilities, due to size, power, or cost considerations.

3.3.7 Operator Use Independence

There should be no assumption about how an operator will, or should, use an unmanned system. Field expedient solutions to unforeseen problems may require bending or breaking existing models of operator use.

3.3.8 Communications Independence

There are many methods of communicating, each with different characteristics such as bit rate, error rate, latency and maximum distance. Different types of unmanned systems, different types of missions, and even different phases of a single mission, may require different communications methods. No assumption should be made about how communications will be carried out by the unmanned system.

3.3.9 Autonomy Level Independence

Unmanned systems will exhibit varying levels of autonomy, as described in [NIST-ALFUS]. Support for low levels of autonomy will involve communicating low order data and commands, such as “Apply ten percent propulsive power”. However, as levels of autonomy increase, higher order data and commands can be used, such as “Go stealthily to the east side of hilltop H before local sunrise”.

3.4 Architectural Views

The three views in AFUS are: conceptual, capability, and interoperability.

Each section in the Conceptual Views includes an introduction and some background material. Each concept is concisely described in the first paragraphs of the section. This material includes the background information necessary to understand the motivation for the choice of terms and models. Additional details are then provided in the Definitions and Models sub-sections.

Each capability is fully introduced in the first paragraphs of the section. This material is further elaborated in the Scenarios sub-section. Each capability is illustrated in one or more scenarios. Each scenario is represented in narrative and one or more models, either textual or graphical. The primary model type is based on the Sequence diagram from Unified Modeling Language 2.0 (UML). The scenarios and models are intended to be sufficiently self-explanatory to need no further guidance on use.

The Interoperability View illustrates various aspects of interoperability across unmanned systems including the motivation for interoperability and the use of standards to achieve it.

4. CONCEPTUAL VIEW

The Conceptual View is the collection of terms, definitions and attributes needed by the Architecture Framework. The definitions must be clear and unambiguous. The concepts are basic and they correspond to several topics as shown in Table 1 and illustrated in FIGURE 2:

TABLE 1 - CONCEPT DESCRIPTIONS

Concept	Topics
Characteristics	Identification, Authority, Safety, and Autonomy
Composition	Platform/Vehicle, Communications Equipment, Sensors, Actuators, and Emitters
Knowledge	Measurements, Detection, World Model, Time, Space, Mechanics, Energy, and Status
Actions	Decide, Plan, Collaborate, Move, Actuation, and Environmental Effects

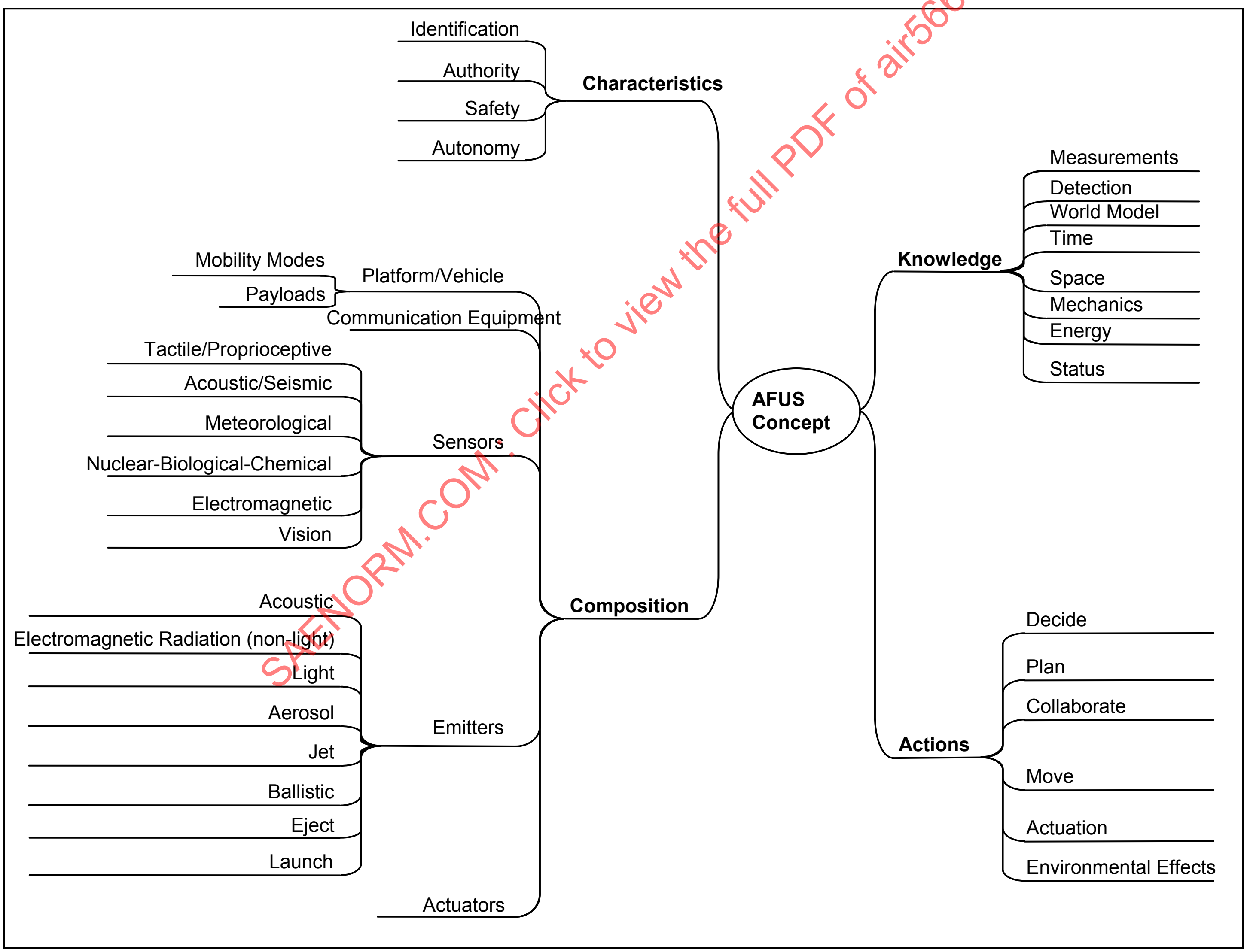

FIGURE 2 - AFUS CONCEPTS

4.1 Characteristics

This concept is about the identification, authority, safety, and autonomy of an unmanned system.

4.1.1 Identification

Any entity, such as an unmanned system or a Command and Control system, must have a means of identification. Entities often have a human-readable name. In order to participate in authentication schemes, entities are issued credentials that can help prove their identity. Examples of an entity name are: an air vehicle's tail number, a ground vehicle's bumper number, or Vehicle Identification Number (VIN).

An authentication scheme consists of five elements: the entity, a distinguishing characteristic of that entity (its credentials), a point of service the entity wishes to access, a proprietor of the authentication data, and an authentication mechanism. An entity's distinguishing characteristic is something it knows (password) or something it has (token). A point of service is an access point on a remote entity that offers a service. The proprietor either issues the distinguishing characteristics (e.g., certificate) or agrees to use existing ones (e.g., password).

There are three primary patterns for authentication schemes suitable for use in the unmanned systems domain: direct, indirect, and off-line. In the direct and indirect patterns, the point of service has access to an authentication service which may be based on secret or public cryptography. For a direct authentication scheme, the authentication service is local to the point of service; for indirect, it is accessed remotely.

The off-line pattern is based on public cryptography provided by a public key infrastructure (PKI). PKI uses (independent) certificate authorities (the proprietors in this pattern) who issue signed digital certificates to each entity that must authenticate. Certificates are (encrypted and) exchanged in order to authenticate. [SMITH02]

4.1.2 Authority

An authority is a right, delegated or given, to perform a specific action on a resource. A principal is the combination of an entity, its authentication credentials, and its collection of authority. Credentials include a representation of a principal's authority, as described in 4.1.1. A designator is a representation of a resource's existence and how to access it.

Authorization is the act of granting or revoking authority. Authorization is considered discretionary if any principal can transfer or grant authority to any other principal. It is non-discretionary if only certain entities can do so.

An authority scheme is a set of mechanisms and processes for authorization of principals within a realm.

Ambient authority is a characteristic of an authority scheme that allows authority to be exercised without explicitly presenting credentials. Without ambient authority, a principal must explicitly select (and present) the appropriate credentials when wishing to perform an action on a resource.

The Principle of Least Authority (POLA) states that a principal should be granted only enough authority to fulfill its assigned responsibilities. In other words, authority should be handed out only on a "need to do" basis. POLA dictates that designation should not automatically confer any authority.

Containment is a characteristic of an authority scheme to prevent unwanted transfer or delegation of authority from one entity to another. Containment cannot be achieved if:

- designation automatically confers authority and designations cannot be restricted; or
- an entity can use the credentials issued to another entity.

Stealth operations demand that entities avoid divulging their existence. So an unmanned system must not respond to a communication from an entity that does not demonstrate sufficient authority.

4.1.3 Safety

Safety is an essential concept to all aspects of unmanned systems. A mishap might result from an unmanned system encountering a hazard. The probability and severity of the mishap occurring together form *risk*. Risk management is the act of reducing overall risk to a *mishap risk acceptance level* through mitigation and other activities.

Safety risks are part of any program's overall cost, schedule, and performance, but this is particularly true for unmanned systems. Planning for safety during a system design process is critical to avoid future mishaps, which in the case of unmanned military systems can include loss of life, serious injury, and equipment damage, seriously jeopardizing mission success. Safety engineering practices must be uniformly applied throughout the design process to manage, mitigate, or eliminate identified hazards. [OUSD07]

4.1.4 Autonomy

Autonomy is an unmanned system's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned by its human operator(s) through designed Human/Computer Interaction or assigned by another system with which the unmanned systems interacts. Autonomy is characterized into levels by the factors of mission complexity, environmental difficulty, and level of Human/Computer Interaction to accomplish the missions. [NIST-ALFUS]

For an unmanned system to be autonomous, it must perceive the world and itself, be aware of the "values" in what it perceives, communicate with the outside world, interact with its environment and other agents (other unmanned systems or humans), maintain a knowledge base, have a decision making process, be able to make short-term and long-term plans, achieve goals of varying degrees of import, and learn about itself and its environment.

The unmanned system may perceive the world in many ways though hardware. Collecting those byte streams of data and making sense of it through image recognition, auditory recognition, shape recognition, and so on, allow the data to have meaning. Being able to fuse that data into a collective whole through sensor fusion allows the system to gain a more accurate and comprehensive understanding of the world around it.

Beyond mere perception, the unmanned vehicle must be "aware" of what the things it perceives actually mean. Perceiving a human as an obstacle is one thing, but knowing a human's capabilities, its likely behavior, and comparing this human to others it has seen allow the system to recognize it as a human. The same can be said for the environment it perceives as well as itself and what internal data it accesses actually means.

Communicating with the outside world allows an unmanned system to perceive the world as an active participant rather than a nihilistic audience of one. By communicating with other agents directly or indirectly, the unmanned system may shape the world in ways impossible to do by itself. Further, it allows the system to learn more about the world beyond its perception, just as a human learns more about the world beyond his view by communicating with other humans.

Maintaining and updating a knowledge base allows the system to develop a memory of past objects it has seen and events it has experienced. Shapes, environments, maps, laws, and other information may then be recalled on the fly or in advance of a goal or mission. As new outcomes to previous decisions are realized, this information is then stored into the knowledge base, creating a perpetual "living document" of all the unmanned system has witnessed.

Making short-term and long-term plans may play itself out through navigation, communication, evaluation, simple or complex strategy, and a host of other problem sets. Setting a plan to achieve a goal or complete a mission is the "job" of an unmanned system. Carrying out plans by using its knowledge base, perception, and recognition of its environment and agents not only allows the unmanned system to fulfill its role, but also to learn from the experience to perform the next plan or mission with more wisdom and care.

4.2 Composition

This concept is about the physical make-up of the unmanned system: its platform, modes of mobility, types of sensors, available computational power, available fuel and power, etc.

4.2.1 Platform/Vehicle

Physical unmanned systems have an infrastructure, or platform, that contains or supports the various devices, mechanisms, and stores needed by the unmanned system.

A payload is a container or device that is (temporarily) mounted to a (typically mobile) unmanned system. Payloads may be carried either internally in bays or externally on pylons or hardpoints. The unmanned system may eject one or more of its payloads. A payload may be under the control of the unmanned system, the unmanned system's controller, or be under third party control. A payload may have self-contained communications capability or rely on the unmanned system to relay communications. The unmanned system may hide or expose the existence of the payload. Under certain circumstances, the payload may require and gain control of the unmanned system.

The platform, or physical body, of an unmanned system has extents and a mass-balance. These may vary with the configuration of the unmanned system. A payload may increase the extents and alter the mass-balance, thus changing the mechanics of the unmanned system.

4.2.2 Communication Equipment

An unmanned system sends and receives signals (messages) to and from other unmanned systems and C2 systems. Entities must be known a priori or be discovered. An unmanned system can act as a communications relay for other entities. Communications characteristics can change during operations. Communications systems may or may not contain embedded security functionality to support encryption and authentication.

See [AIR5645] for background.

4.2.3 Sensors

Unmanned systems sense the world around them through hardware sensors, which respond in specific ways to specific phenomena in the environment. The sensor product is raw sensor data, and is delivered to one or more processors, which produce increasingly higher-order sensor products. Sensor products codify information from the environment and can be used to reason about the environment.

Sensor types include tactile, proprioceptive, seismic, acoustic, chemical, electromagnetic, laser, and vision. Passive sensors perform their detection without affecting or altering the environment. Active sensors use some form of emission to detect the reflection or other effect that emission has on the environment. Active sensors may be mono-static (emitter and receiver are co-located), bi-static (emitter and receiver are physically separated), or multi-static (similar to bi-static, with multiple receivers).

4.2.4 Actuators

An actuator is a mechanical device that can change shape in response to a signal. Much of what we think of that is robotic is made possible by use of actuators. An actuator can be a simple device that has linear movement (prismatic) or rotation (revolute), or it can be an articulated manipulator arm with many joints and links.

The classic manipulator is an "arm" of a robotic system used to position an end-effector. Another common manipulator is a pan-tilt unit often used to position a directional sensor or emitter.

4.2.5 Emitters

An emitter is a device that can discharge a substance or energy into the environment. Examples include radio, RADAR, LASER, loudspeaker, liquid jet or disruptor or sprayer, ballistic weapons, launchers for various self-propelled devices, and so on. Table 2 lists some possible emission types and Table 3 lists some possible delivery mechanisms.

TABLE 2 - EMISSION TYPES

Emission Type:
Acoustic
Liquid/Gas: Water, Pepper Spray, Paint
Electro-Magnetic: Heat, Radiation, RF, Light (Visible, IR, UV, Laser)
Particles/Solids: Smoke, Chaff
Munitions: Kinetic, Explosive

An emitter can be a hardware device that generates a signal via some form of electromagnetic or acoustic energy pulse (a waveform), which is intended to convey information (via modulation) to a receiver. An emitter can also be a device that discharges a solid object on a ballistic trajectory; drops objects by way of gravity (special case of ballistics); shoots a jet of water or other liquid, a disruptor; etc. Most weapons fall into the class of emitters. But whether weapon or not, all emitters require extensive safety precautions, both mechanical and procedural, in design and operation.

TABLE 3 - DELIVERY MECHANISMS

Delivery Mechanism:
Radiation
Aerosol
Jet
Ballistic
Drop, Jettison, Eject

4.3 Knowledge

This concept is about the information an unmanned system stores, communicates, and reasons about. All knowledge inherently has a degree of uncertainty which must also have a representation that can be stored, communicated, and reasoned upon along with that knowledge.

4.3.1 Measurements

Measurement is the processing of raw sensor product within a customary unit which may include the combination of numerous raw sensor products. For example, the combination of raw sensor product from a laser emitter/receiver pair, and a timer, can yield distance traveled via the relationship of $d=vt$ where v is the speed of light, c, perhaps corrected for atmospheric variations.

The term quantity appears in several definitions from [PSD02] and has been replaced with the term measure to clarify meaning. A Measurement is the result of transforming raw sensor data into a quantity with an associated unit of measure.

4.3.2 Detection

Detection is a computational process resulting in correlation of raw sensor product within an a priori ontology. Detection includes various computational processes ultimately resulting in correlation of sensed observations with internally generated expectations. It includes recognition of entities existing and events occurring in the world and any significant differences between sensed observations and expectations can be used to update the world model. [ALBUS]

In order for an unmanned system to perform certain tasks, it must be able to recognize, or detect, objects and events. For example, if an unmanned system is tasked to navigate through an urban environment, then that system must be able to recognize roads, lanes within roads, other vehicles, etc. Detection is a high-level of sensory processing. It may use raw sensor products, but more often uses measurements processed from the raw sensor products. A priori information is also often needed so that the unmanned system can compare these measurements to templates of the object or event being detected.

4.3.3 World Model

A world model is a logical representation of the real world, internal to an unmanned system. It may include models of objects, events, classes, tasks, agents, portions of the environment, and the unmanned system itself [NIST-ALFUS]. These models are its best estimate of the state of the world based on data that is given to it a priori, as well as what it perceives with its sensors and receives from its communication gear. The world model includes all of the knowledge that is distributed throughout the unmanned system and sent from the unmanned system to another subsystem [ALBUS].

The world model is the intelligent system's best estimate of the state of the world. The world model includes a database of knowledge about the world, plus a database management system that stores and retrieves information. The world model also contains a simulation capability that generates expectations and predictions. The world model provides answers to requests about the present, past, and probable future states of the world. The world model provides this information service to the behavior generation system element in order to make intelligent plans and behavioral choices. It provides information to the sensory processing system element to perform correlation, model matching, and model-based recognition of states, objects, and events. It provides information to the value judgment system element to compute values such as cost, benefit, risk, uncertainty, importance, and attractiveness. The world model is kept up to date by the sensory processing system element. [MEYSTEL]

A geographic information system (GIS) is a system for capturing, storing, analyzing and managing data and associated attributes which are spatially referenced to the earth. An important aspect of the world model is representing the data spatially. This benefits the unmanned system when performing certain tasks such as path planning, navigation, and target acquisition and tracking. Spatial components in a world model can be represented by points, lines, and areas. The two most common methods of storing spatial data are called raster data models and vector data models.

The raster data model is an abstraction of the real world where the basic units of data (points, lines and areas) are represented using a matrix of cells or pixels. The raster model uses the grid-cell data structure where the geographic area is divided into cells identified by rows and columns. In the simplest form, each cell of a raster data model contains a value for the element. Any cell not containing a feature would have the value of "0". In more sophisticated systems, the cell value is a label that links to the record as an attribute. The following information must be known when using raster data:

- Grid Extent – the number of rows and columns of the grid
- Grid Resolution – the size of each grid cell
- Georeferenced Information – the coordinates of the origin of an object with respect to a world coordinate system.

In the vector data model, features are represented in the form of coordinates. The basic units of data (points, lines and areas) are composed of a series of one or more coordinate points. For example a line is a collection of related points and an area is a collection of related lines.

- A point is defined by a single group of coordinate values. A point normally represents a geographic feature that is too small to be represented as a line or area.
- A line is defined by an ordered list of coordinate pairs defining the points through which the line is drawn.
- An area is defined by the lines that make up its boundary. Areas are also referred to as polygons.

The resolution of a vector data model combined with the size of the feature determines what basic unit of data will represent the feature. For example, a lake could be represented as an area (by lines that make up its boundary), or it could be represented as a point if the resolution of the data model is low enough (such as a map of the entire United States).

When modeling spatial data, the type of data that is being modeled (either in a raster cell or by a point, line or area in a vector model) is called a feature class. A feature class represents a categorization of types of geospatial data. For example, occupancy, free space, objects, roads, terrain, buildings, orthoimages, etc. all represent distinct feature classes. It may be more intuitive to consider these feature classes as different layers of geospatial data within the knowledge store.

4.3.4 Time

Temporal measurements are among the most important concepts in the domain of unmanned systems. Time is measured on a time scale using time tags, intervals, durations, and frequencies [NELSON01].

Typically, each entity in the unmanned system domain will have its own clock. Therefore, time coordination problems must be addressed. "*A man with a watch knows what time it is; a man with two watches is never sure*". - Segal's Law

An important time scale is scenario time, used for running simulations and test scenarios. Scenario time is based on some other time scale (usually UTC or GPS), but provides for pausing, resetting and resuming the epoch at arbitrary points.

Temporal operators work on more abstract notions of time: always, eventually, next time, and until. [HALPERN95]

A time scale has an observable repeating interval, such as the rotation of the earth or the count of resonance of an atom. Marked at certain points along this continual scale are notable events called epochs. An epoch is equated with specific time tag, for example midnight UTC January 1, 1970. Most time scales begin with an epoch chosen to correspond with a specific time tag on another time scale.

The scale interval is either based on Earth's rotation, Earth's revolution around the Sun or constructed from some atomic property. The most common scale interval in use is the International System of Units (SI) second. Based on historical studies of Earth's rotation, the SI second was "made equivalent to an astronomical second based on a mean solar day of 86 400 seconds in about 1820." [Nelson 2001] Today, the SI second is defined as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom. [NIST08]

While there are many defined time scales, the most familiar are Universal Time (UT and UT1), Global Positioning System (GPS), International Atomic Time (TAI), Terrestrial Time (TT), and Coordinated Universal Time (UTC).

UT, formerly known as Greenwich Mean Time (GMT), has a scale interval based on Earth's rotation angle at the Prime Meridian (0 degree longitude), Greenwich, UK. Unfortunately, UT has many fluctuations due to factors that include polar motion and seasonal variations. UT1 is UT corrected for polar motion, making it suitable for use in precise navigation. Earth Rotation Angle (ERA) is a set of stellar observations from which UT1 is derived.

GPS, TAI, TT, and UTC are all atomic time scales, using the SI second as scale interval. GPS time is implemented by atomic clocks in the GPS ground stations and GPS satellites. TAI is the statistical combination of a large collection of atomic clocks. TT is defined to be the proper time on the geoid of the Earth and is based on TAI and is used primarily for astronomy.

UTC is not based solely either on Earth's rotation or on atomic clocks, but is a compromise between the two. There is a need for a universal civil time scale that counts SI seconds, but is (very) close to UT1. The scale interval of UTC is the SI second (by following TAI). When UTC drifts too far away from UT1 (the current tolerance is 0.9 SI second), the epoch of UTC is adjusted. Since 1972, the adjustments to UTC have been whole SI seconds, called leap seconds. By the end of 2010, twenty-four leap seconds had been added to UTC.

UTC is broadcast around the world encoded in radio emissions. Also encoded on those emissions is an approximation of the difference between UTC and UT1 (DUT1) for use in systems that need accurate (to 0.1 second) ERA data.

All time tag and interval representations must indicate the time scale used (e.g., UTC). All time duration and frequency representations must indicate the scale interval used (e.g., SI second). Time data without indication of the time scale or scale interval used is meaningless.

4.3.5 Space

Spatial measurements are also important concepts in the domain of unmanned systems. Coordinate systems measure distance and direction with respect to rigid bodies. Coordinate systems are comprised of coordinates and a reference point (origin), and can be nested to an arbitrary degree, each one having an origin defined in its “parent” coordinate system. Three commonly used coordinate systems are spheroid, Cartesian, and North-East-Down (NED), all of which are right-handed.

Spheroid coordinate systems are based on mathematical models of a celestial body (often Earth). The model usually describes an ellipse that is rotated fully to extrude the surface of the spheroid. A geoid is based on a spheroid with refinements to the surface model, usually taking into account local gravitation variations across the surface. World Geodetic System 1984 (WGS-84) is a commonly used geoid definition.

The Cartesian coordinate system defines x, y and z (each on its like-named notional measure) measured in meters. For Cartesian position systems, one measure is chosen to point at or align with something of interest. For instance, the x measure is often aligned with the centerline of a mobility platform, but it can also point North.

A frequently used (in aerospace applications) Cartesian coordinate system is the North-East-Down (NED) where (as suggested by the name) the x axis points North, the z axis points down (normal to the surface), and (to be right-handed) the y axis points East.

Along with position it is often necessary to know the orientation (or rotation) of an object. Any three-dimensional rotation can be represented by three angles (Euler angles). The convention used for measuring the three angles can be specified by giving the name, unit of measure (almost always radians) and the axis of rotation for each angle. The order of axes is essential to preserve the meaning of the measures. If the measures are applied to a different order of axes, it will often result in a completely different orientation.

A commonly used convention is the Aerospace Set which names the angles yaw, pitch, and roll, all measured in radians. Yaw is measured around the z axis first, followed by pitch measured around the resulting y axis, followed by roll measured around the resulting x axis. In this denotation, yaw should not be confused with the naval usage in which it is sometimes taken as a deviation in course,

The specific position and orientation of a body in a coordinate system is called a pose.

The size, or extents, of a three-dimensional object can be given by a set of minimum and maximum measures for each axis. The height, length, and width represented by the extents can be interpreted as the difference between the maximum and minimum measures on each of the x, y, and z axes.

The terms altitude, elevation, and height are often erroneously used interchangeably. The preference in this Framework is for altitude to be used for distance above (or below) the reference surface, elevation to be used for the angle from horizon (as defined in 2.3), and height to be used for the vertical component of a body’s extents.

Depth (similar to altitude) is a measure below a reference surface and should be used for underwater measures.

For the measure of extents, the minimum must be less than or equal to the maximum. A zero thickness body can be expressed with minimum equal to maximum for that axis measure.

4.3.6 Mechanics

Many unmanned systems move or must reason about motion. The field of physics called mechanics deals with motion (kinematics) and forces that cause motion (kinetics or dynamics). A full treatment of mechanics is beyond the scope of this Conceptual View, but kinematics and elements of kinetics can be used to measure and reason about the motion of bodies.

The forces from movement of the environment can affect motion of the platform. The velocity components are modified by the environment motion resulting in a course, or heading. The vector from a pose to a desired position is a line of bearing, which may differ from the heading due to environment motion.

4.3.7 Energy

Unmanned systems require energy and must carry consumable, stored energy or else harvest energy from the environment for self-contained operation.

Energy is used for powering electronic and electrical equipment and powering mobility systems. Energy sources include consumable and rechargeable storage mechanisms and energy conversion mechanisms.

Consumable energy sources include disposable battery cells, liquid hydrocarbon fuel for combustion engines, fuel cell reactants such as hydrogen and oxygen, fissile material for fission reactors, etc. Energy can be directly stored or converted to storable energy. Energy storage mechanisms include rechargeable battery cells, capacitors, and flywheels.

Some characteristics of energy sources are: fuel type, fuel unit, fuel capacity, fuel consumption rate unit, fuel consumption rate (nominal, standby and maximum), operating temperature (nominal, standby and maximum), energy capacity (nominal, standby and maximum), and power output (nominal, standby and maximum).

Energy source state can include: current operating temperature, current fuel and coolant temperatures and pressures, the lifetime and current operation times, current energy capacity, current power output, current fuel consumption, etc.

4.3.8 Status

Unmanned systems can have status. Status is a measure of conditions of the system or subsystem.

Status may be directly comprised of single or multiple measurements (such as an temperature sensor), or it can be indirectly composed using measurements to generate another metric of status (such as the "overall health" of the system). A simple example of status is overheating. Overheating can be measured via a temperature sensor. As the temperature rises, the ability of the system to perform its intended capability is diminished.

4.4 Actions

This concept is about the logical and physical activities an unmanned system can perform to make changes in the world.

4.4.1 Decide

A decision is a final product of the specific mental/cognitive process of an individual or a group of persons/organizations which is called decision making; therefore it is a subjective concept. It is a mental object and can be an opinion, a rule or a task for execution/application.

Decision making is the cognitive process leading to the selection of a course of action among alternatives. Every decision making process produces a final choice. It can be an action or an opinion. It begins when a system needs to do something but does not know what. Therefore, decision making is a reasoning process which can be rational or irrational, and can be based on explicit or tacit assumptions.

For most unmanned systems, decisions can be made at the navigational, communicational, and tactical levels.

At the navigational level, an unmanned system creates a route from a known origin to a known destination by gathering known mapping information from its knowledge base and placing constraints that its awareness and knowledge subsystems assign. Additionally, dynamic changes in the route allow for on-the-fly changes due to new information, which will then assign weights and continuously update itself to build better routes based on currently available information, which could change the route if necessary. Furthermore, to get from origin to destination, the unmanned system will miniaturize the route into a series of smaller nodes and edges, in a checkpoint-to-checkpoint fashion, to weigh "costs" to minimize the overall "cost" of the route.

At the communicational level, as the unmanned system communicates with other systems in either a team-oriented environment or as an adversarial approach, the system may exchange data at a high-level, deliver sensor data it receives for a low-level sharing of information, or partially process the data along with some annotation of its contents for a medium-level approach. Such communication allows unmanned systems to communicate ideas and develop strategies at a higher level.

At the tactical level, the unmanned vehicle may develop strategies at a higher level. Goal achievement, mission completion, and decomposing a selected task into a series of smaller steps allow for successful conclusion of its efforts.

4.4.2 Plan

Planning is the process of “thinking” about the activities required to create a desired future on some scale. In humans, this thought process is essential to the creation and refinement of a plan, or integration of it with other plans. The term is also used to describe the formal procedures used in such an endeavor, such as the creation of data or ad hoc or premeditated teaming to distribute important issues to be addressed, the objectives to be met, and the strategy to be followed.

At a navigational level, route planning allows the unmanned systems a route from an origin to a destination at a high-level, from waypoint to waypoint or checkpoint to checkpoint at a medium level, and at a vector-to-vector at a low-level, all the while optimizing and making dynamic changes on the fly.

At a tactical level, sudden dangers from active agents and the environment may make themselves known, and enacting contingency plans or envisioning “what-if” scenarios create the need for an unmanned system to meet these challenges.

4.4.3 Collaborate

Umanned Systems and their operators can collaborate both in planned or unplanned interactions. Sharing system awareness with other unmanned systems allows unmanned systems to poll one another for lacking sensor data, to share perception data with others at some or all times, and even to make decisions with other systems at a group level.

Planned collaboration generally consists of teams of systems and people linked in a common purpose. A group of platforms in itself does not necessarily constitute a team. There are, however, many components that make up a team, like manager and agents. Platooning, goal sharing, and mission sharing are all examples of unmanned vehicles collaborating in a team environment.

Teaming requires successful application of communication, perception sharing, perception interpretation, goal achievement, and mission completion.

When an unmanned system perceives itself, its environment, or other agents, it may wish to send all or partial data available to all interested parties. Additionally, part of the challenge is in how much data may be transferred between systems and how quickly this transfer can be accomplished. Performance measures may be necessary for critical decisions, and limited perception requires less bandwidth for transferring data between systems. Similarly, some perception information may be pre-processed in advance, depending on context. As a team, there is a natural synergistic effect in how awareness may be distributed among its members. An unmanned system capable of data integration and fusion is able to essentially combine its perception data with that of others and make independent and joint decisions.

Joint goal achievement and mission completion requires collaboration and coordination of unmanned systems. Leaders/followers, managerial/staff, pointman/scout, unified whole, leader/wingman and other possible configurations allow unmanned systems to pull together unique or duplicated capabilities to make more informed decisions in terms of independent and joint tasks.

Collaboration does not necessarily imply teaming, but may be an opportunistic interaction between platforms. Such unplanned groups can opportunistically take advantage of information sharing, enhancing each platform’s or team’s ability to complete missions. Groups in fact could create teaming relationships in an ad-hoc fashion in order to better perform a mission or save a potentially failed mission.

4.4.4 Move

Mobility is the capability for an unmanned system to change its location or orientation under its own power.

Mobility requires one or more propulsion mechanism to convert energy into motion. Some propulsion mechanisms are wheels, tracks, legs, wings, propellers, screws, rotors, jets, thrusters, sails, etc.

The platform geometry must enable the propulsion mechanism to produce the desired motion. A mobility platform will often have multiple control surfaces that produce or alter motion. Air platforms typically have rudders, ailerons, flaps, etc. Water platforms can have rudders, dive planes, etc. Even ground platforms can have control surfaces in certain cases. Ground platforms are described by wheel, track, or leg configurations including track width, wheel base, number of legs, etc.

The envelope describes the performance capabilities of the mobility platform when using a propulsion mechanism. These capabilities include maximum ceiling altitude and nominal cruise altitude of air platforms, maximum pitch and roll of ground platforms, and maximum depth of underwater platforms.

4.4.5 Actuation

Actuation includes articulation, manipulators, and actuators in general.

Actuation is the act of causing linear or angular motion by some mechanism (actuator). The motion of an actuator is called slue with maximum and minimum slue limits, and maximum and current slue rate. Unmanned systems require actuators to manipulate devices such as antenna masts, landing gear, mobility control surfaces, cameras, and manipulator arms.

A manipulator is a chain of links connected at joints with angular or linear actuators. A manipulator base is anchored on the platform and has one or more end effectors. Manipulators are often described as having a given number of degrees of freedom (DOF). The number of joints, the combination of joint types, and their physical arrangement determine the degrees of freedom.

A Pan Tilt Unit (PTU) is a specialized manipulator that typically has two angular joints which are orthogonal to one another. One joint performs “panning”; the other performs “tilting.” PTUs are a common mount for cameras and other devices that must be “pointed” at arbitrary positions within an arc around the unmanned system.

Each leg of a legged ground mobility platform can be treated as a sequence of actuators.

4.4.6 Environmental Effects

Environmental Effects alter the environment in some way. This includes grasping, pushing, and/or pulling objects and generating emissions such as heat, light, sound, and substances. These effects introduce a radiation, force, or substance into the environment that alters it in some way. Effects can be classified by its type, the type and geometry of the target and the delivery mechanism.

Moving alters the environment by repositioning some material from one location in the environment to another. One example is to move solids – usually achieved by pushing with a blade or articulation or picking/scooping, lifting and placing/dumping with articulation. Another example is to move liquids or gasses – usually achieved by pumping or blowing.

Cutting alters the environment by drilling or severing something in the environment, such as cutting along a line, drilling at a point, or grabbing a sample and storing it in a storage receptacle on board the platform.

Clearing is the mitigation, neutralization, or removal of a radiation or substance in the environment. Examples include decontamination of chemical, biological, radiological, or nuclear agents, and the disabling of mines, explosive ordnance, or Improvised Explosive Devices.

5. CAPABILITY VIEW

The Capability View defines behaviors of unmanned systems.

5.1 Discovery

Discovery is learning about other entities for the purpose of possible interactions. Discovery capabilities include, but are not limited to, enumeration, identification, location, and classification of entities and their capabilities.

5.1.1 Scenario: Discover Remotes

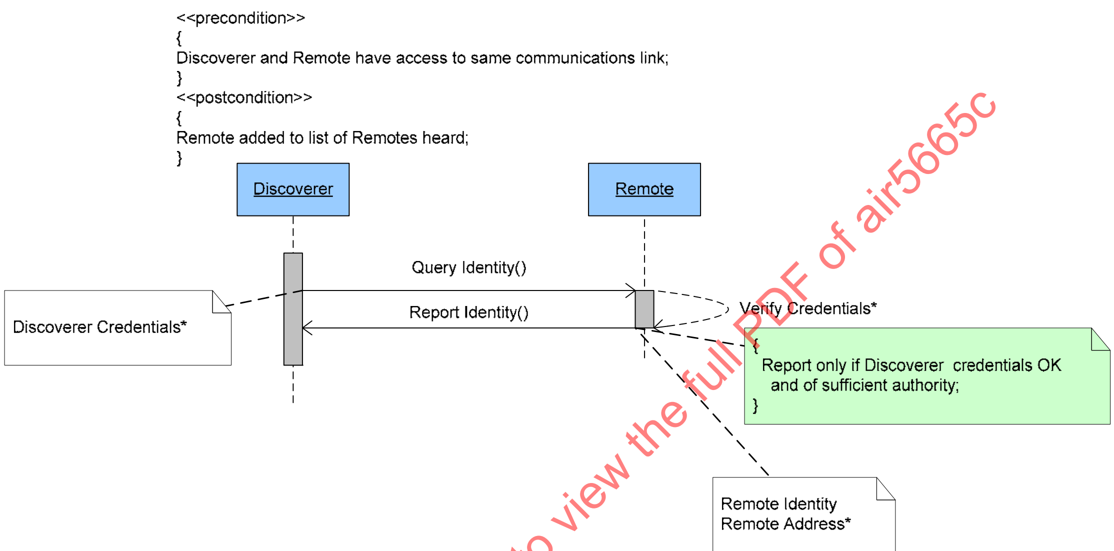

FIGURE 3 - SCENARIO DISCOVER REMOTES

Discovering Remote systems can occur in any of several ways. All remote systems might be listed in a static configuration file or database, and thus all known a priori. Or, the remote system might wait for an appropriately authenticated Query Identity message then reveal their identity and therefore their presence to the Discoverer (and any other entity listening on the communications link), see FIGURE 3 for illustration.

The remote's identity is required so the Discoverer can differentiate between multiple remotes. Depending on the nature of the communications link, the remote may need or wish to include its address in the Report Identity message.

5.1.2 Scenario: Discover Remotes on Trusted Link/Network

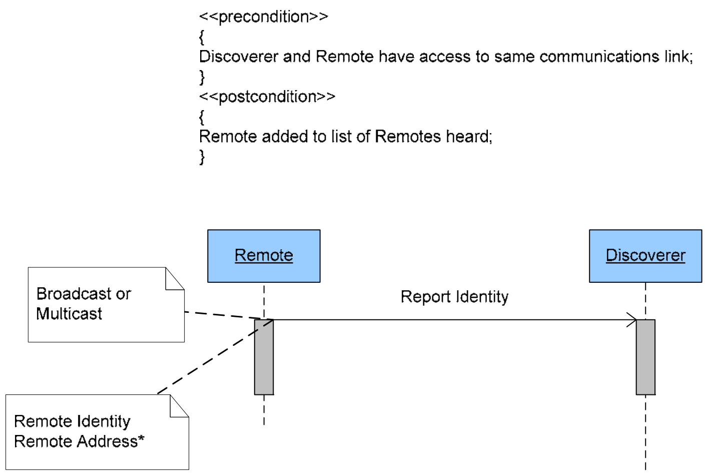

FIGURE 4 - SCENARIO DISCOVER REMOTES ON TRUSTED LINK/NETWORK

If discovery is to take place on trusted communications links, the remote system could announce itself and all announcements overheard by the Discoverer can be added to its list of remote systems, see FIGURE 4 for illustration.

5.1.3 Scenario: Discover Capabilities

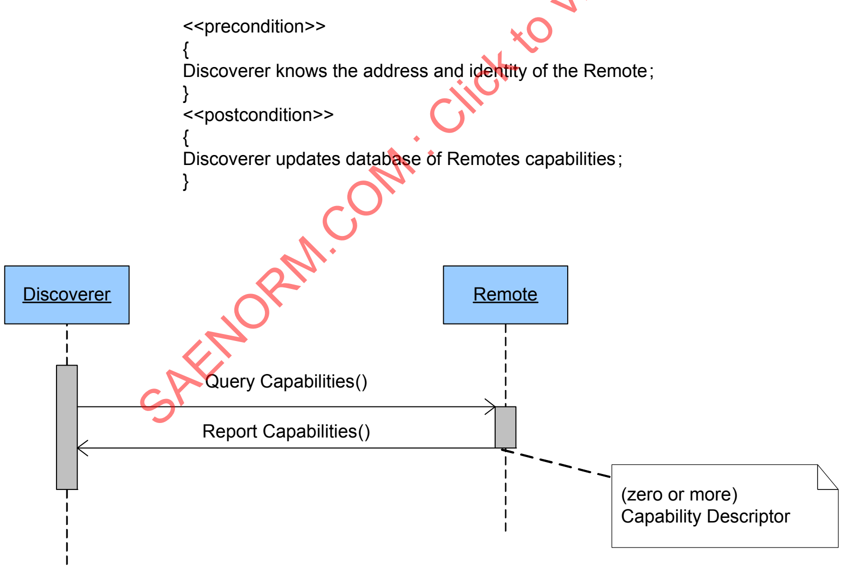

FIGURE 5 - SCENARIO DISCOVER CAPABILITIES

Another essential function is to provide a list of capabilities in a standard form. Requestors of that list can use it selectively to request access to individual capabilities, see FIGURE 5 for illustration.

5.2 Communication

Communication is about exchanging information with the world outside the unmanned system, as well as internally within it.

5.2.1 Scenario: Establishing Communications

Information about number and type of communications resources, such as receivers, transmitters, antennas, pedestals, emission types and characteristics, maximum links of each type, etc.

5.2.2 Scenario: Report Communication Status

Communication networks for mobile systems are often fluid and dynamic. Once communications have been established, it may be necessary for clients to query the status of a link to a particular remote system, or receive regular transmissions from the remote system to ensure a reliable link.

<<invariant>>
{
Network permits communication between Remote and Requestor
}
<<preconditions>>
{
Communication link established
}

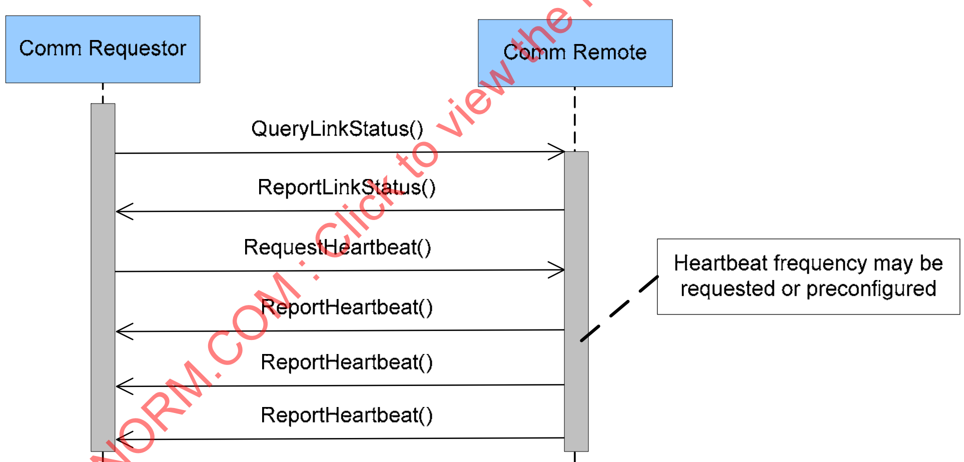

FIGURE 6 - SYNCHRONOUS AND ASYNCHRONOUS COMMUNICATION REPORTING

5.2.3 Scenario: Communication Relay

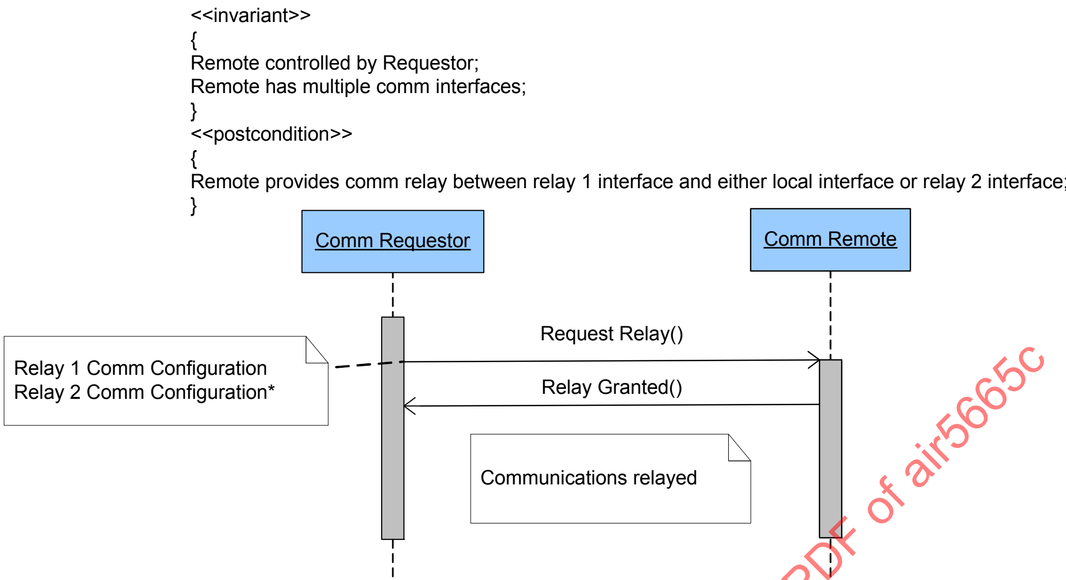

FIGURE 7 - SCENARIO COMMUNICATION RELAY

An unmanned system may be equipped to serve as a communication relay, either as its sole mission, or in addition to its other capabilities. If such a capability is present, then there must be a protocol for sharing information about communication relay capability, such as number and type of simultaneous relays. Some types of relay are Full and Half Duplex and Store and Forward, see FIGURE 7 for illustration.

Full Duplex relaying occurs in real time with reception on one communication link and transmission on the same or a different communication link. The two links may use different modes, frequencies, antennas, media, etc.

Store and Forward relaying is not real time and requires all message traffic to be stored locally on the unmanned system to be later transmitted on the same or a different communication link.

5.3 Access

Control capabilities include gaining, transferring, and relinquishing access to systems and their capabilities. Access control provides a common baseline to which application-specific information assurance, encryption, and anti-tamper capabilities can be added. Although the primary goal of SAE AS-4 Standards is to facilitate interoperability, access control provides means to prevent an unexpected and unwanted exchange from taking place.

Several essential concepts underlying this set of capabilities are Authentication, Authorization and Credentials. Authentication provides a trusted means of ensuring a party's identity, roles and organization affiliations. Authorization determines what that party can and cannot do or know based on its Authentication. Throughout the following section Credentials are passed about and verified. These Credentials are an abstraction that conveys, via a trusted mechanism, the party's identity, roles and organization affiliations. The actual implementation details for Credentials, Authentication and Authorization may differ from that depicted here, but the essential concepts will not differ.

5.3.1 Scenario: Bootstrap Credentials

Most unmanned system elements have an ability to verify authentication credentials of remote entities and to maintain schemes for verifying whether remote entities are authorized for controlling or gaining access. It is necessary to bootstrap the unmanned system element with its own credentials and to configure the schemes for both verifying external credentials and checking authorization.

Some unmanned system elements may have authorization bootstrapped only at the factory. Others may be field-bootstrapped for increased flexibility.

5.3.2 Scenario: Gain Access

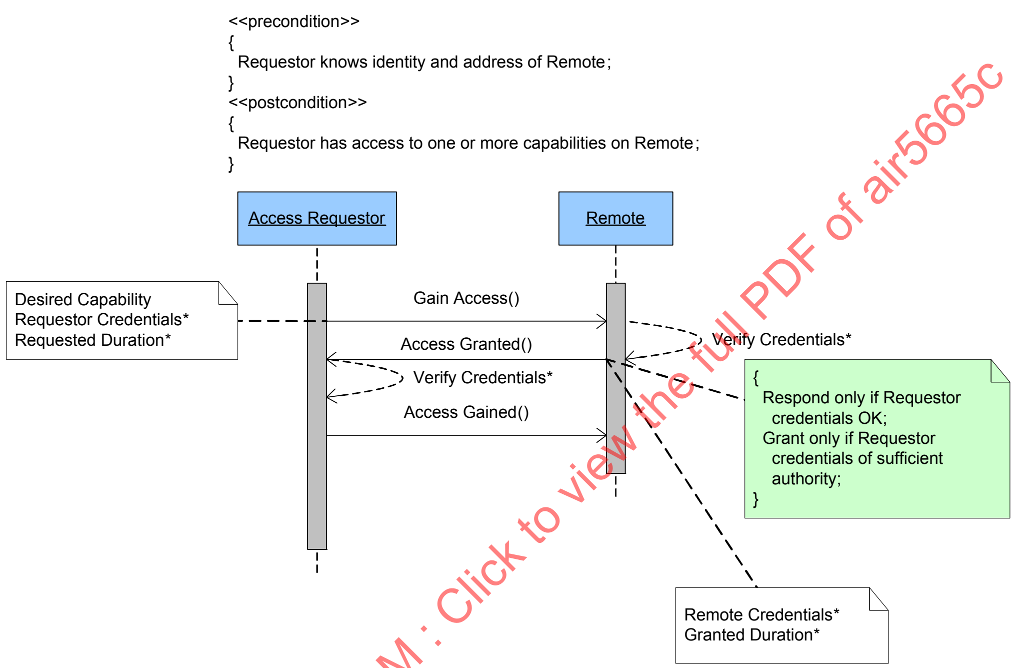

FIGURE 8 - SCENARIO GAIN ACCESS

Access to a Remote's capabilities allows one to request and receive information about or from those capabilities. For instance, access to a Remote's Localization capability allows one to request the Remote's Global Pose, either one time, or to have the Global Pose sent upon the occurrence of certain events.

Given sufficient authorization, it may be possible to gain access to some or all of a Remote's capabilities. The first access request is typically for the remote system's list of capabilities. The Requestor could also ask for access to all the remote system's capabilities. Otherwise, the Requestor must specify the exact capabilities to which it is requesting access, see FIGURE 8 for illustration.

If not on a trusted communications link, it is desirable to send and verify credentials for sufficient authorization as part of requesting access.

It is possible for either the Requestor or the Remote to specify a maximum duration for the access. The Remote can respond with shorter access duration than the Requestor requested if necessary.

Access can be terminated in one of several ways. The Requestor can relinquish access. If provided, the access duration can expire and cause the Remote to terminate access. Or, the Remote or its Controller can revoke access for a variety of reasons.

5.3.3 Scenario: Modify Access

<<precondition>>
{
Controller wishes to grant access to Remote to Third Party;
}
<<invariant>>
{
Controller controls Remote;
}
<<postcondition>>
{
Third Party has access to Remote;
}

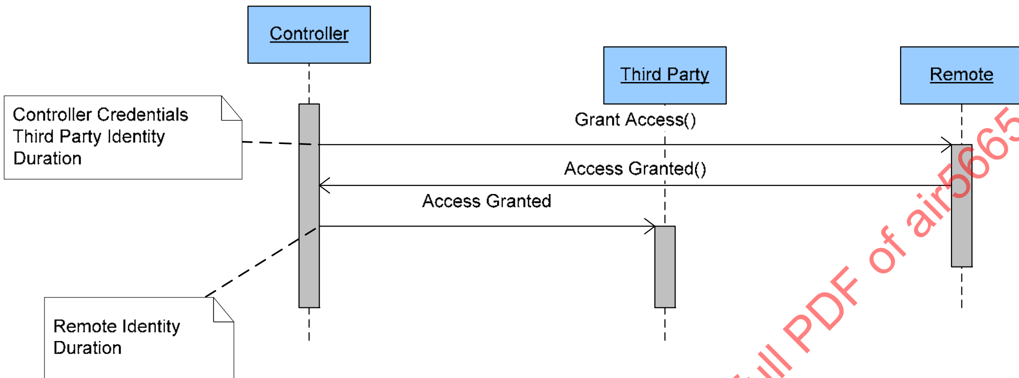

FIGURE 9 - SCENARIO GRANT ACCESS

The Controller of a Remote can modify (grant or restrict) access to any of the Remotes capabilities. The resulting grants and restrictions are put immediately into effect and are retained for later authorization checks, see FIGURE 9 for illustration.

<<precondition>>
{
Third Party has access to Remote;
Controller wishes to revoke access to Remote to Third Party;
}
<<invariant>>
{
Controller controls Remote;
}
<<postcondition>>
{
Third Party no longer has access to Remote;
}

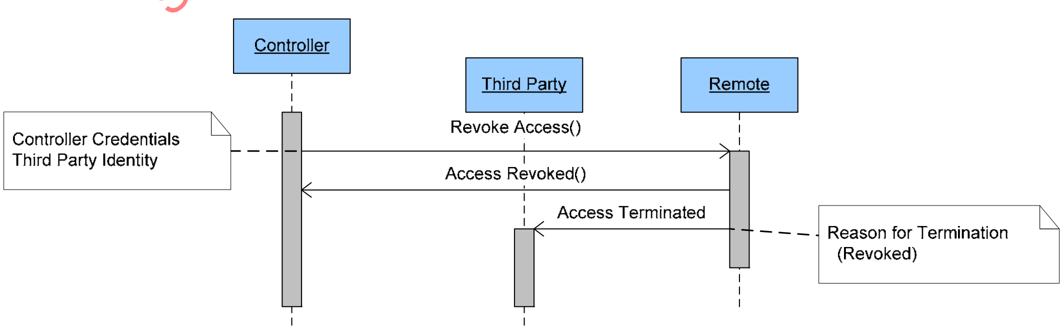

FIGURE 10 - SCENARIO REVOKE ACCESS

Each of a Remote's capabilities may have an authorization requirement necessary for a Requestor to gain access or control of that capability, see FIGURE 10 for illustration.

5.3.4 Scenario: Event Reporting

<<precondition>>
{
Event for Criteria not already setup between Requestor and Source;
}
<<invariant>>
{
Requestor has gained access to Source;
}
<<postcondition>>
{
Source sends Events for Criteria until Event Cancelled;
}

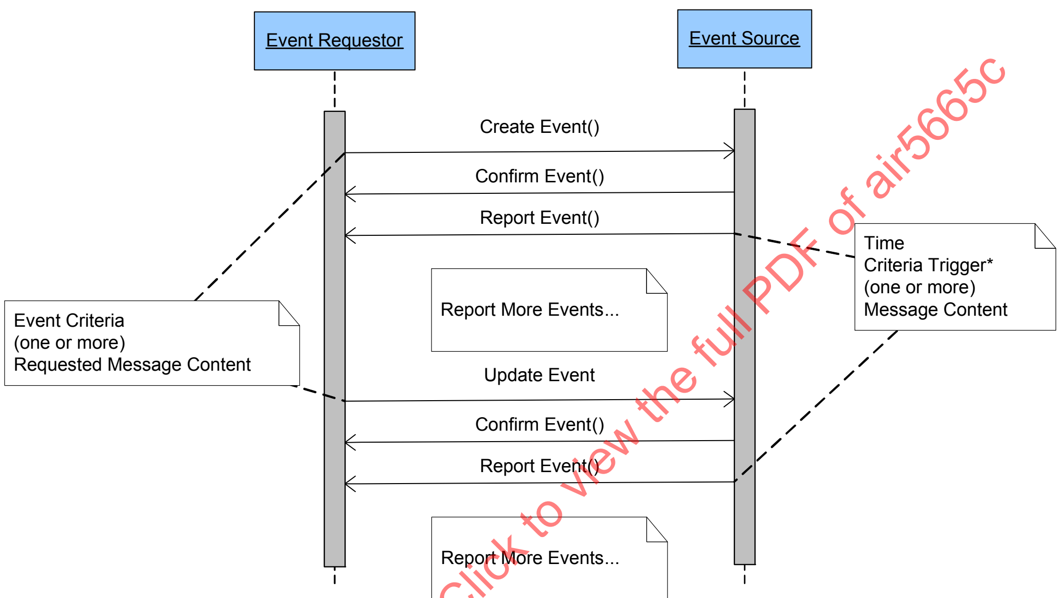

FIGURE 11 - SCENARIO EVENT REPORTING

Having access or control to a Remote's capability allows a Requestor to obtain information from that capability. Information can be obtained in a number of ways. A one-time request will get a one-time response. Also, a request can be made for scheduled, periodic responses, see FIGURE 11 for illustration.

Event criteria can be cancelled.

5.4 Control

Control capabilities include gaining, transferring and relinquishing control of systems and their capabilities.

5.4.1 Scenario: Gain Control

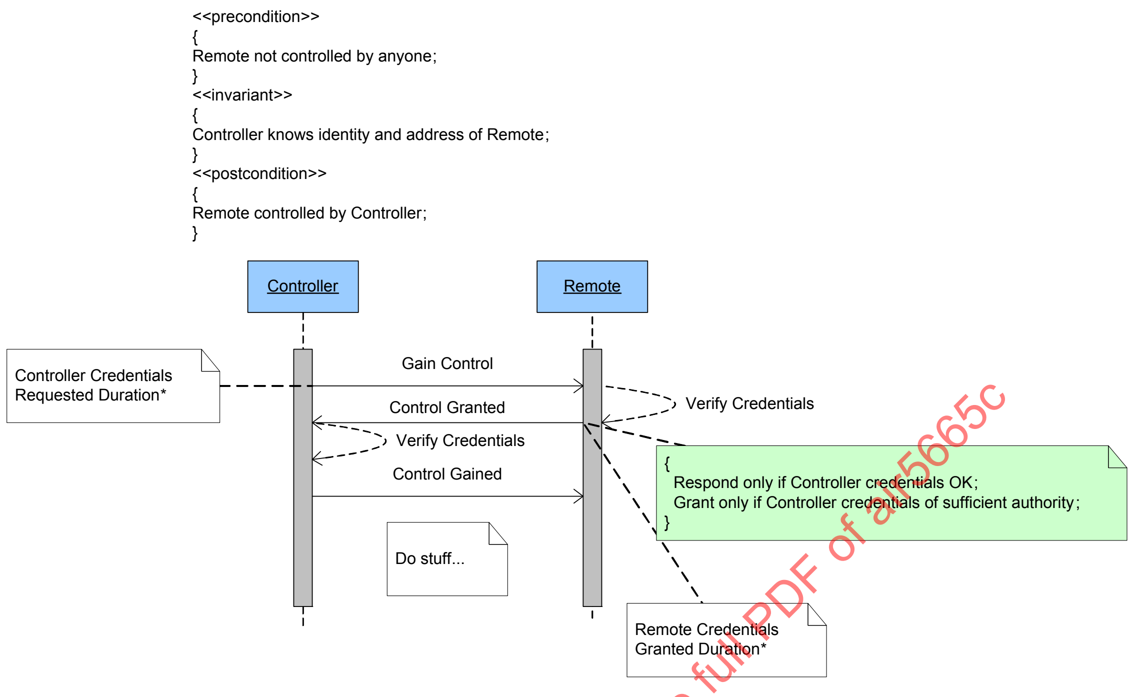

FIGURE 12 - SCENARIO GAIN CONTROL

Control over a Remote or one of its capabilities imparts the ability to command the Remote to perform actions on behalf of the controller, such as maneuvering, changing configuration of sensors, shutting down, etc.

Given sufficient authorization, it is possible to gain control over a Remote, or one or more of its capabilities. Once granted, Control is mutually exclusive, but control of individual capabilities can be delegated to one or more Third Parties.

If not on a trusted communications link, it is desirable to send and verify credentials for sufficient authorization as part of requesting control.

It is possible for either the Requestor or the Remote to specify a maximum duration for the control. If necessary, the Remote can respond with shorter access duration than the Requestor requested.

5.4.2 Scenario: Terminate Control

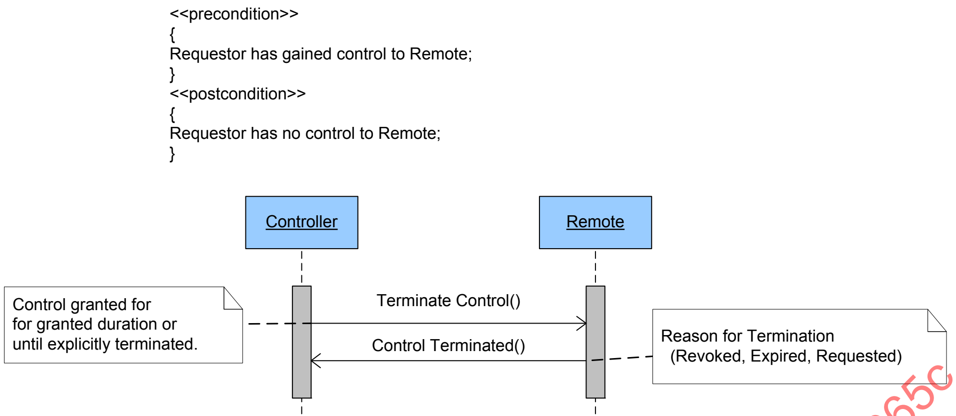

FIGURE 13 - SCENARIO TERMINATE CONTROL

Control can be terminated in one of several ways. The Requestor can relinquish control. If provided, the control duration can expire and cause the Remote to terminate control. Control of the remote might be overridden by a Second Controller. Or, the Remote can revoke control for a variety of reasons, see FIGURE 13 for illustration.

5.4.3 Scenario: First Party Control Transfer

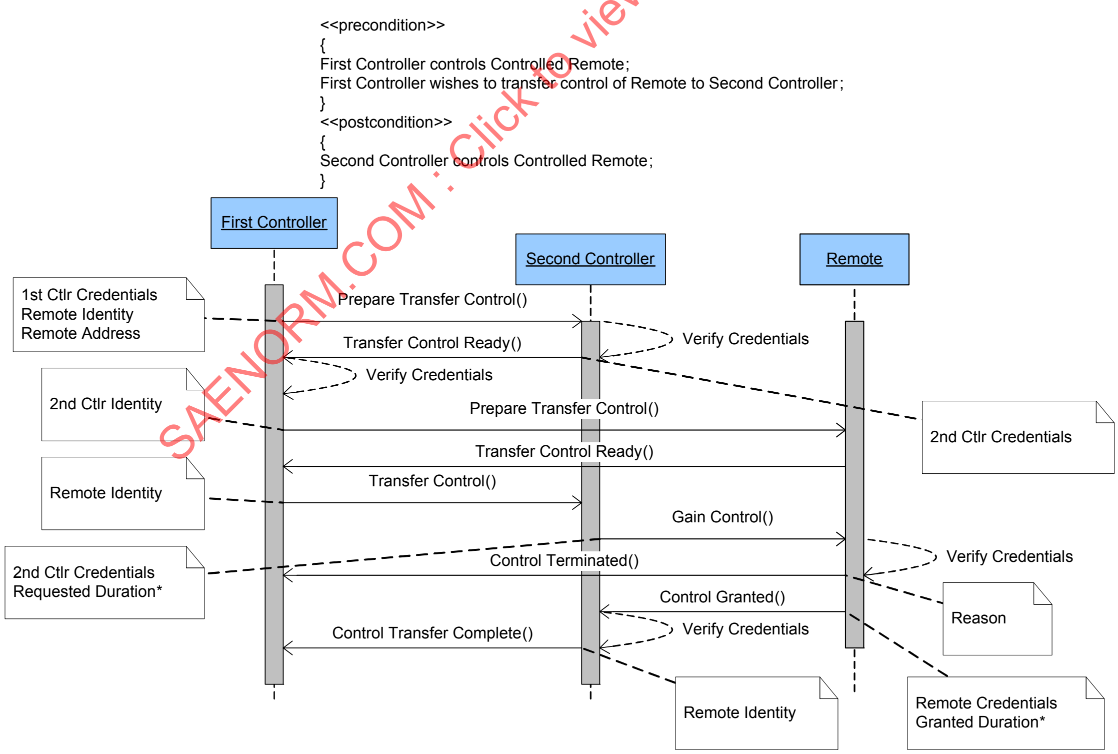

FIGURE 14 - SCENARIO FIRST PARTY CONTROL TRANSFER

The Controller of a Remote will occasionally need to allow another Party to control the Remote. This can occur under a wide variety of circumstances, such as when Remote crosses a jurisdiction boundary, or when the Controller is compromised and can no longer effectively control Remote, etc.

First Party Control Transfer is a three-way handshake between the First Controller, the Remote, and the Second Controller. Both the Second Controller and the Remote must be alerted that a transfer is going to take place. The Remote must be informed of who the new Controller will be and Remote and Second Controller must establish trust, see FIGURE 14 for illustration.

5.4.4 Scenario: Cooperative Second Party Control Transfer

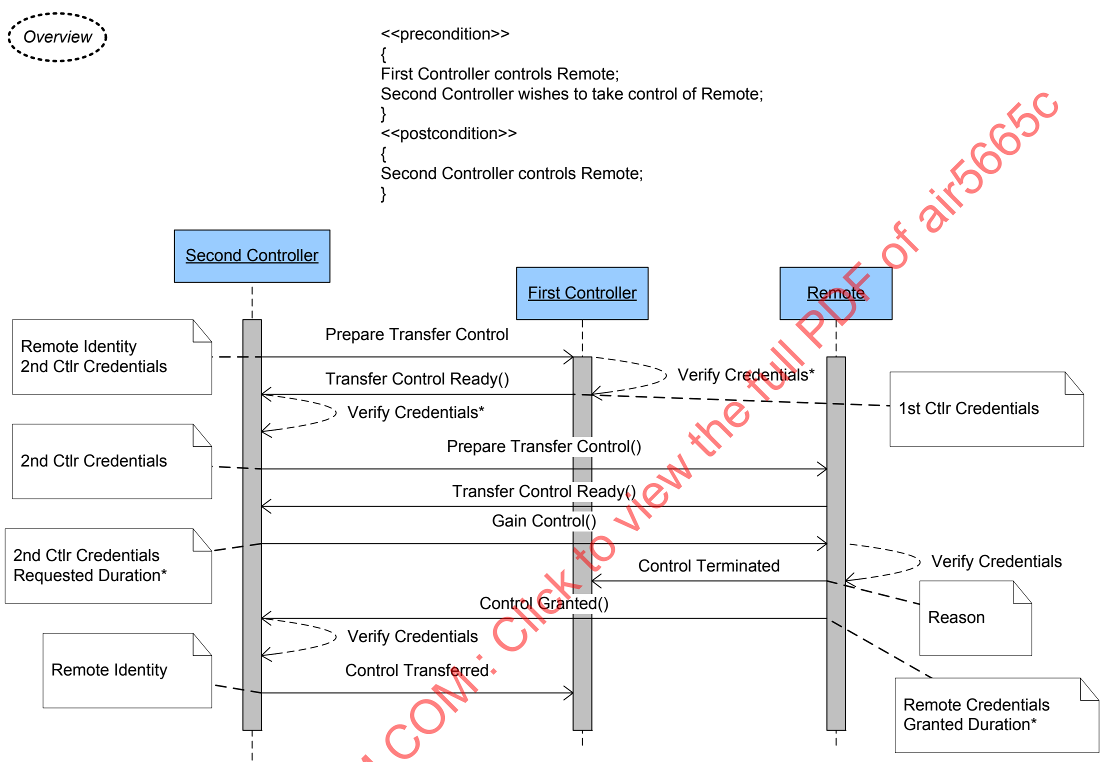

FIGURE 15 - SCENARIO SECOND PARTY CONTROL TRANSFER

A second party will occasionally need to take control of a Remote away from the First Controller. This can occur for a variety of reasons, such as for a change in authority structure above the Remote.

Second Party Control Transfer can either be a three-way handshake with a responsive, cooperative First Controller, or a two-way handshake if the First Controller is unresponsive or uncooperative, see FIGURE 15 for illustration.

5.4.5 Scenario: Second Party Control Override

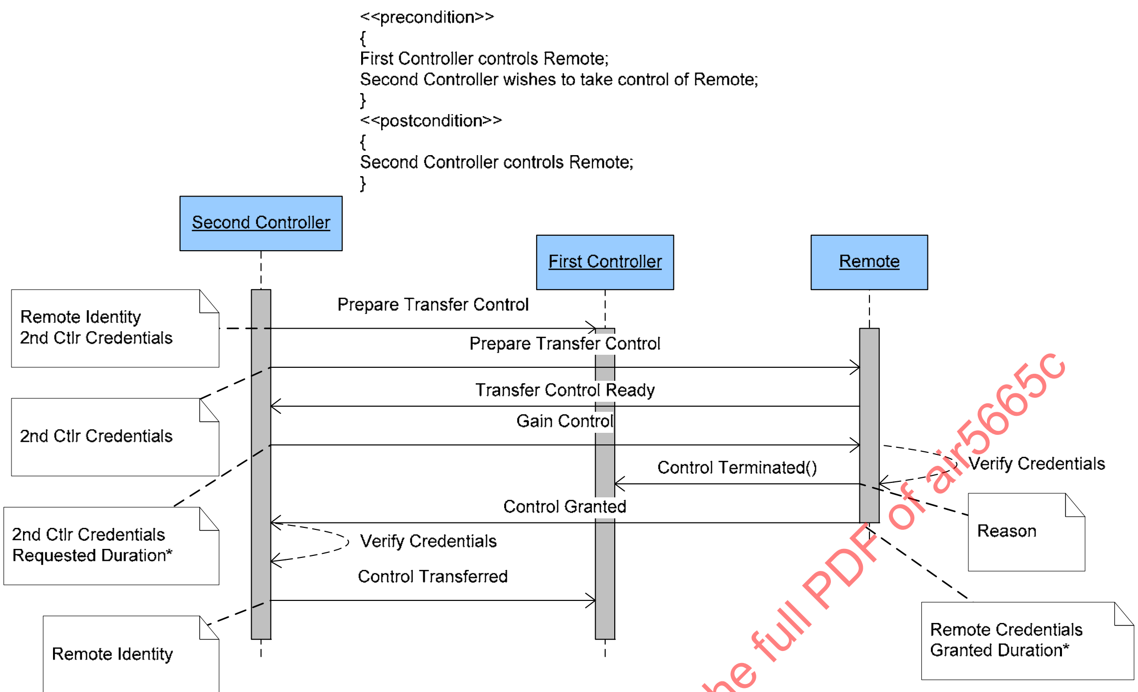

FIGURE 16 - SCENARIO SECOND PARTY CONTROL OVERRIDE

A second party will occasionally need to take control of a Remote away from an unresponsive or uncooperative First Controller, see FIGURE 16 for illustration.

5.5 Platform

Unmanned systems are embodied in a platform. A platform has a number of characteristics, including its physical dimensions, signaling devices, sensing devices, bays and hardpoints for payloads, etc.

5.5.1 Scenario: Query Platform Information

Unmanned systems may need to provide information about their physical dimensions, such as height, width, length, mass, center of mass when unladen, origin of platform coordinate system, maximum mass, etc.

5.5.2 Scenario: Activate Platform Signals

Unmanned systems may need to provide information about the signaling devices they have access to, such as lights, audible alarms, Emergency Locator Transponder (ELT), etc.

5.5.3 Scenario: Query Platform Power

Unmanned systems may need to provide information about and means to control their power sources, such as batteries, engines, fuel cells, gas tanks, etc.

5.5.4 Scenario: Query Payload Information

Unmanned systems may need to provide information about the number and type (bay or hard point) of payload locations, their mass/size capacities, available power and/or communications ports, etc.

5.6 Mobility

Mobility encompasses a variety of capabilities that permit an unmanned system to maneuver. Each Mobility capability focuses on a different abstraction used to express the mobility instructions to the unmanned system.

Several essential concepts underlying this set of capabilities are Coordinate System, Position, Orientation and Pose. Coordinate System is a system for representing a Point in an n-dimensional space, usually with an axis for each dimension. The Coordinates of a Point are the components of a tuple of numbers used to represent the location of the Point in a specific Coordinate System. The Orientation of a rigid body is the components of a tuple of numbers used to represent the rigid body’s rotation about the various axes in a specific Coordinate System. Pose is the combination of Coordinates and Orientation in a specific Coordinate System.

All movement is bracketed by Start Movement and Stop Movement messages. The diagrams all show the Start Movement message arriving before any other capability-specific movement message, but the sequence is not important. If capability-specific movement messages arrive first, then movement will be delayed until a Start Movement arrives. Likewise, if there are unprocessed capability-specific movement messages pending when Stop Movement message arrives, then the remaining capability-specific messages are ignored (or paused) and movement is ceased.

5.6.1 Scenario: Establish Contingency Mobility

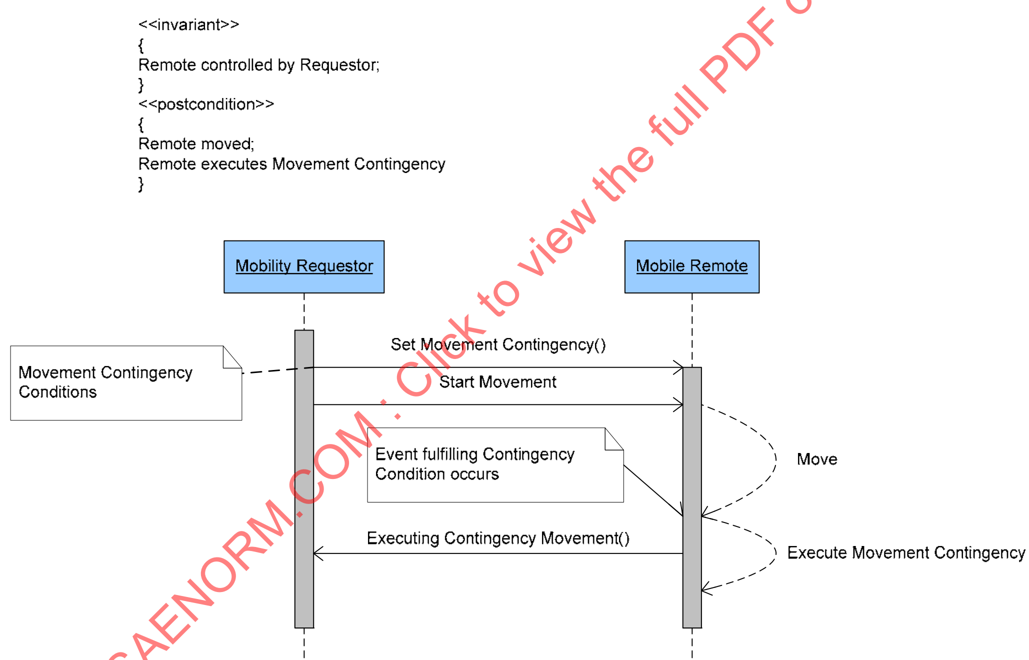

FIGURE 17 - SCENARIO CONTINGENCY MOBILITY

Several types of unmanned vehicles must maintain a certain type and amount of movement to avoid suffering damage or uncontrolled drifting. When movement is stopped, or if all capability-specific movement messages have been performed, these types of unmanned system must have a contingency movement behavior, see FIGURE 17 for illustration.

A Movement Contingency is typically a form of Station Keeping.

5.6.2 Scenario: Perform Pose Mobility

<<invariant>>
{
Remote controlled by Requestor;
}
<<postcondition>>
{
Remote moved;
Remote executes Movement Contingency
}

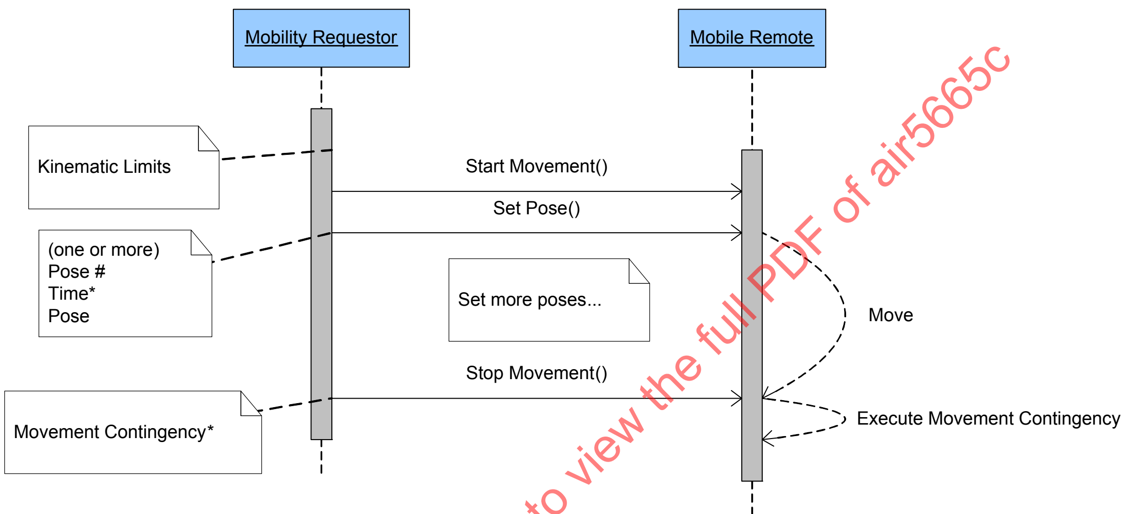

FIGURE 18 - SCENARIO POSE MOBILITY

Pose Mobility is the capability of a Mobile Remote to be commanded to move from its current Pose to a new Pose. Exactly how the unmanned system proceeds from Pose to Pose is not specified. An expected Time can be included so that the unmanned system is expected to arrive at the specified Pose exactly at the specified Time, see FIGURE 18 for illustration.

Waypoint Mobility is a subset of Pose Mobility with limited or no kinematic limits or time and space tolerance constraints.

5.6.3 Scenario: Perform Station Keeping Mobility

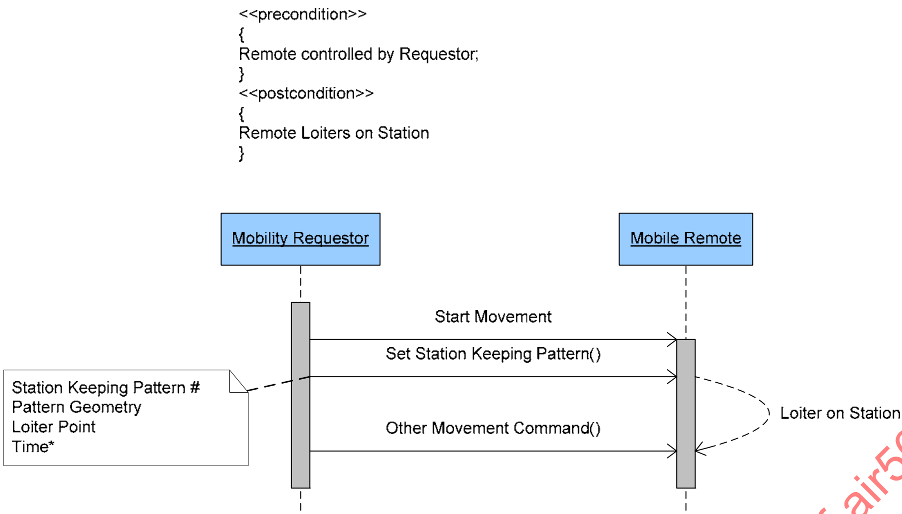

FIGURE 19 - SCENARIO STATION KEEPING MOBILITY

Station Keeping, also called Loiter, is the ability for an unmanned system to maintain a Pose (within a tolerance) by executing a simple movement pattern, see FIGURE 19 for illustration.

Different types of unmanned systems require different movement patterns to perform Station Keeping. UGVs can maintain a Pose by not moving at all. UAVs must perform a variety of loops or figure-eight patterns to periodically pass through (and thus maintain) a Pose. UUVs, USVs, and UAVs capable of hovering can keep station by applying just enough movement to oppose the effects of winds and currents. UGVs can maintain Orientation while Station Keeping, but due to the typical propulsion systems in UUVs, USVs and UAVs, these unmanned systems cannot easily or continuously maintain a constant Orientation.

Station Keeping is often used to establish a rendevous location prior to recovery of a remote platform.

5.6.4 Scenario: Kinematic Mobility

<<invariant>>
{
Remote controlled by Requestor;
}
<<postcondition>>
{
Remote moved;
Remote executes Movement Contingency
}

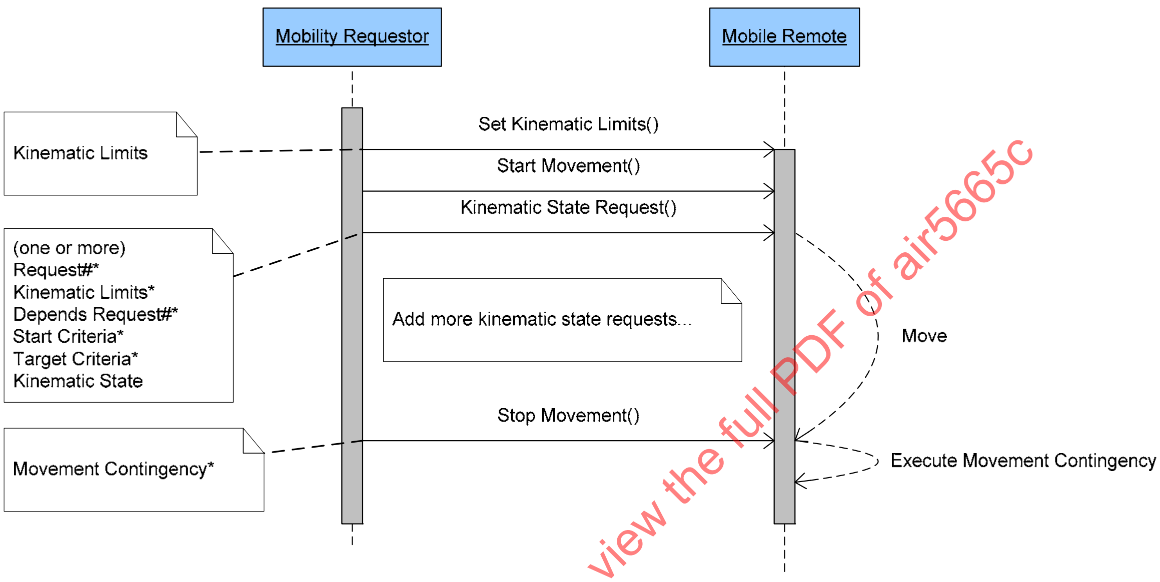

FIGURE 20 - SCENARIO KINEMATIC MOBILITY

Kinematics of a rigid body is the description of the translational and rotational motion of the rigid body in a specific Coordinate System, emphasizing the derivatives of position. Kinematic Mobility is the capability to specify in engineering units both instantaneous and future kinematics of the unmanned system, see FIGURE 20 for illustration.

An important element of Kinematic Mobility is the ability to specify kinematic limits. These limits instruct the unmanned system not to exceed a certain amount of velocity, acceleration, or jerk on any or all of its axes.

5.6.5 Scenario: Path Mobility

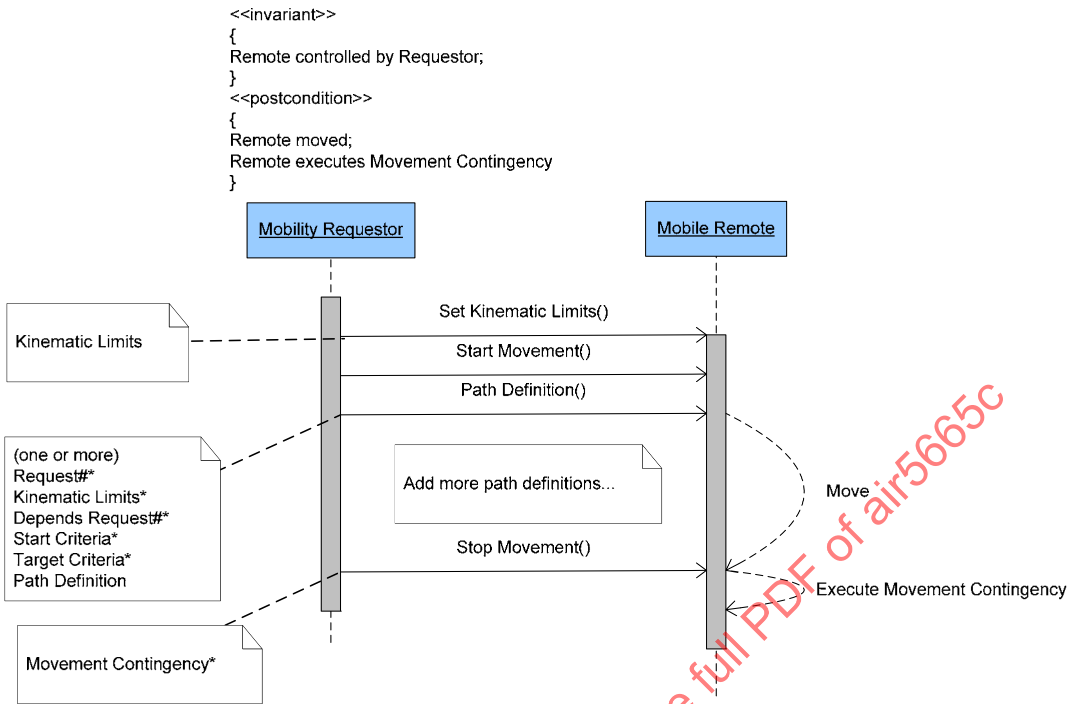

FIGURE 21 - SCENARIO PATH MOBILITY

Path Mobility is much like Pose Mobility, except that a more sophisticated description of the unmanned system's travel path is fully specified, see FIGURE 21 for illustration.

5.6.6 Scenario: Primitive Mobility

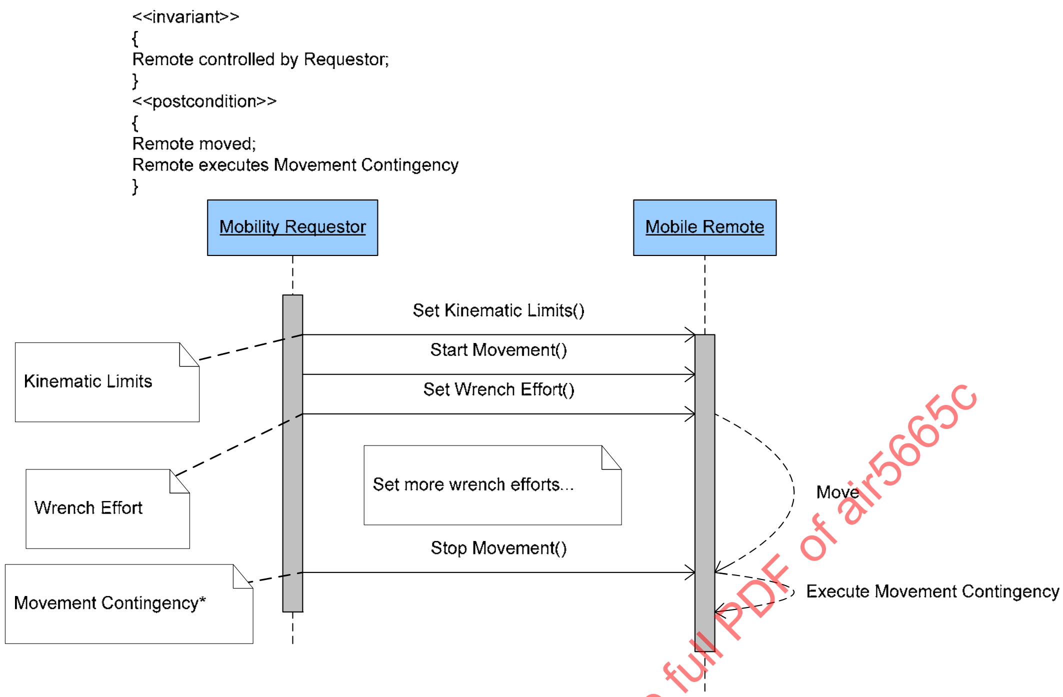

FIGURE 22 - SCENARIO PRIMITIVE MOBILITY

Primitive Mobility controls platform mobility actuators by mapping command elements to the specific mobility controls of a vehicle, see FIGURE 22 for illustration.

All element values are a percentage. Thus, wishing to command half of the potential forward propulsive power would result in an element value of fifty percent. All elements of Primitive Mobility are not necessarily applicable to a particular platform. For example, a typical wheeled vehicle can be controlled with only three elements of the wrench command: Propulsive Linear Effort X (throttle), Propulsive Rotational Effort Z (steering), and Resistive Linear Effort X (brake).

5.6.7 Scenario: Perform Homing

Homing is similar to Pose Mobility except that the new Pose may be specified with respect to a moving frame of reference. Examples of homing include docking of a platform with a host, mid-air refueling, or smart munitions. Homing may be active or passive. In active homing systems, the platform must find and track the target autonomously. For passive systems, information about the motion of the destination is provided by an external system.

Homing generally requires the platform to move toward the host or target. For maintaining a fixed pose with respect to a moving frame of reference, see ‘Convoy’.

5.7 Articulation

Articulation permits an unmanned system to move an end effector in reference to the unmanned system in order to grasp, push, and/or pull objects or to simply position a device in a specific pose relative to the platform or the environment. There are currently three articulation movements: Primitive, Path, and Pose. Primitive articulation is the positioning of the end effector via a human interface device (e.g., joystick) by an end user. Path articulation is movement over the same path, continuously. Pose articulation is orienting the end effector.

5.7.1 Scenario: Query Articulator Information

Information about the number and type of Articulators and their configuration.

5.7.2 Scenario: Perform Pose Articulation

Similar to Pose Mobility, Pose Articulation permits directing an articulator by defining a series of Poses for its end effector.

5.7.3 Scenario: Perform Path Articulation

Similar to Path Mobility, Path Articulation permits defining a path for the articulator Tool Point to travel, possibly repeatedly.

5.7.4 Scenario: Perform Primitive Articulation

Similar to Primitive Mobility, Primitive Articulation permits directing Articulator motion by percentage efforts of each joint in the Articulator.

5.8 Mission Planning

Mission Planning is the ability to reason about the current state of the World Model and create a plan of action to achieve some desired new state in order to meet specific objectives while operating under specific constraints.

5.8.1 Scenario: Define Mission Plan

In order for a system to plan a mission, it must have mission goals specified. Mission goals can be described in terms of world state (e.g., the blue crate should be on top of the red crate) or in terms of system state (e.g., the system has deployed its solar panels). In some cases, these two views overlap (e.g., the system should be at location X,Y at time T).

In addition to mission goals, a system may have constraints on the mission imposed by map and route definitions. By limiting the possible states of the system through map definitions, and the transitions between those states through route definitions, the search space of the mission plan may be reduced. Examples include limiting mobility to a predefined radius around the start location, or preventing a mission plan from traveling against a tidal current.

Constraints on mission plans may also be imposed by specifying one or more mission behaviors.

In order to support multiple mission definitions, a unique mission identifier should be used. This allows subsequent commands to be applied only to a specific mission definition. Requests to modify, execute or delete a mission definition based on an invalid or unknown identifier should be rejected.

5.8.2 Scenario: Alter Mission Plan

The Alter Mission Plan operation allows the requestor to modify an identified mission plan. This operation may insert an entirely new sub-plan within the existing plan, or it may replace an existing sub-plan with a new sub-plan including a blank sub-plan. Altering a mission plan may not replace the existing plan's start point. In some cases, requests to alter an executing mission plan may be rejected if the current state of the system does not permit those changes.

5.8.3 Scenario: Execute Mission Plan

Once a mission has been defined, requestors with appropriate levels of authority may initiate execution of a mission plan, based on the unique identifier. During execution, missions may be paused, resumed, or cancelled.

5.8.4 Scenario: Report Mission Plan Status

The current state of a mission plan should be available at any point during its execution. This may be represented as a percent complete, a list of remaining objectives, estimate of time remaining, or other quantitative assessment of progress. Systems may also report success or failure with respect to identified mission objectives.