PROTOCOLS FOR ROBOT COMMUNICATIONS:
TRANSPORT AND CONTENT LAYERS

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ABSTRACT

Communications between cooperating robots can be facilitated by using suitable communications protocols. This paper discusses many of the considerations that impact the form of such protocols, beginning with a primitive model of cooperating robots and their interactions with each other and the external environment. Consideration is paid to the role of the robot's internal model of its world, to the different functions of communications between cooperating robots, and to relevant characteristics of the communications environment. A layered protocol structure is presented, consisting of data transport layers borrowed from computer networking technology and task independent and task dependent content layers. Finally, the effects of the communications environment on this structure are discussed.

I. INTRODUCTION

Growing interest in robots adds increasing importance to the area of robot communications and encourages the development of structures to simplify robotic communications processes -- protocols. This discussion is directed toward providing some perspectives on the development of robot communications protocols.

A definition of "robot" is necessary to establish a common ground for discussion. For the purpose of this paper, a robot is any device which possesses sensor(s) and effector(s) and uses these resources to act purposefully, autonomously and continuously. Such a broad definition is supported by common usage and is consistent with Wiener's description of automata [1].

Robot teams offer a number of advantages over a single robot in many situations. It is often cost effective to build many smaller and simpler devices which are individually less capable than a larger robot but when used in concert provide significant more capability. The aggregate sensed and effected domains of a team of robots can be greater than would be feasible with a single robot. Furthermore, the performance of a group of cooperating robots can be more reliable through redundancy (sparing). Modular system design complements the concept of cooperating robots by facilitating a clear division of labor among robots each of which is an expert at one type of task such as painting or welding.

The coordination of a team of robots in a stochastic environment would be impossible without communications, and any but the simplest communications scheme will introduce significant complications into robotic system analysis and design. However, these complications can be significantly ameliorated by structuring the interactions with suitable communications protocols. This paper addresses several aspects of robot communications from a perspective which has been influenced considerably by experience gained from computer networking protocols.

II. PROBLEM

Others have explored the problems and prospects of cooperating autonomous systems to some extent. Nilsson and Raphael [2] examined many issues of a control language for human to robot communications. They suggested some requirements of such a language and many of these requirements were considered in the protocols presented herein. Fikes, et al. [3] discussed the concept of teams of robots, but did not treat robot communications in any detail. Currently, Nilsson, Moore and Sacerdoti [4] are engaged in a study of communications strategies between independent but cooperating computational devices.

The area of distributed problem solving systems shares many issues with that of robot communications. Smith [5] developed protocols for communication between the members of a contract net. However, these protocols apply only to the contract net organization. Lesser and Corkhill [6] discussed a system consisting of distributed problem solvers which can exchange incomplete and possibly incorrect information while still converging on a common solution. However, this system uses centrally controlled shared memory for information exchange, thus avoiding many of the complications introduced by physical communications.

Hewitt [7] and Hewitt and Baker [8] discussed the application of actor theory to distributed systems. Actor theory provides a specialized organization which can be used to analyze interacting systems, but it provides neither tools powerful enough nor a perspective broad enough to permit complete analysis of robot communications.

The purpose of this work is to synthesize and generalize previous related work in the fields of artificial intelligence and computer networking in order to produce a set of flexible and widely applicable protocols to support robot communications. The primary concern is the structure of interactions between separate autonomous devices encountering each other in the environment, rather than with the problem of dividing a task into subtasks that are then allocated to different robots for execution. This is not to imply that the results of this study are not applicable to the communications required to support various distributed problem solving structures. This discussion is directed toward exploring issues of robot communications associated with the data transport protocol layers as well as the layers just above.

A number of assumptions help to define the problem domain and underly the model of robot interactions from which the communications protocols are developed:

(1) a robot is a device which consists of sensors and effectors coupled by processing capabilities

(2) the bandwidth between a robot's sensors, processing and effectors is much greater than the communications bandwidth between the individual robots

(3) the output of a subset of the robot s sensors is a function of the external environment

(4) a subset of the environment is a function of the robot's effectors actions

(5) the output of a subset of the robot's sensors is a function of the robot's effectors' actions

(6) the bandwidth between a single robot's sensors and effectors through the environment is high compared to the bandwidth between robots

(7) each robot possesses a representation of the environment

(8) each robot possesses a goal structure or representation of the desired state of the task environment

(9) a robot's world model consists of representations of the task environment and the goal structures

(10) communicating robots share some commonalities of their respective world models

(11) the mechanisms supporting robot communications can be modeled as a layered structure, with the lower layers (transport) layers providing at least an equivalent to datagram service

While these reasonably general assumptions apply to communications between quite primitive devices (e.g., garage door openers), the real utility of the resulting protocols is likely to be in reasonably complex devices (e.g., those controlled by 8 bit CPUs and up) and more complex task environments, since simple robots functioning in simple task environments do not need to pay the overhead associated with extremely protocol flexibility.

III . THEORY

Robot Systems

As discussed previously, a single robot can be modeled by a device with sensors and effectors which are integrated through a set of processes (i.e., processing elements and programs). A representation for this model which illustrates the direction of information flow through the system is:

(sensors) -> (processing) -> (effectors)

A sensor is a device which transforms energy fluxes from the surrounding environment into some form of internal representation or symbology. Similarly, an effector is a device which transforms internal symbology into effects (or energy fluxes) in the environment. A robot may have any number of sensors and effectors, and both sensors and effectors may be either simple (e.g., thermocouple and resistance heater) or complex (e.g., television camera and sophisticated manipulator) without affecting the resulting analysis. In a sense, the sensors and effectors of a robot are the boundary conditions of the function which projects the sensor inputs into the effector space (i.e., the processing component).

A robot's sensors and effectors are interfaced through some type of controlling device which transforms the sensor inputs into effector outputs to achieve the desired goal. This device is usually one or more digital computers; in the past (and today in a simple robot such as a thermostat) it was implemented as an analog controller representing the robot's control laws.

A digital controller includes both processing (CPU) and memory resources. The memory resources of a robot generally consist of manipulable and nonmanipulable data structures. In simple robots the nonmanipulable structure represents the controlling instructions and associated constant data while the manipulable structure is only sufficient to represent the state of the device at a single instant of time. Such a device would correspond to Culbertson's memoryless robot [9]. More sophisticated robots would have larger manipulable data structures to hold the collections of time ordered events which constitute the world model, as well as nonmanipulable structures for "hardwired" behaviors and goals. Sufficient processing resources must be available to perform the sensor/effector integration and coordination necessary to fulfill the robot's mission. Various aspects of this single robot model are explored in more detail elsewhere [10].

The robot model introduced above, while adequately describing the attributes of a single robot, lacks an explicit means of communication with other cooperating autonomous entities (other robots or humans) since communications resources are just special cases of sensor and effector resources. As a convenience in this discussion, however, the primitive robot model used in this analysis includes communications resources as well as the sensor, effector and processing resources required to produce the behavior desired. This modified primitive robot model is illustrated below.

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(sensors) -> (processing) -> (effectors)
                  !
            (communications)
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A system of cooperating robots can be represented as a collection of these primitive robots communicating to form a "team" that can interact with the task environment through its complement of sensors and effectors to achieve its (hopefully common) goals.

World Model

In order to examine the interactions which can occur between cooperating robots it is necessary to have some model of the knowledge that is stored in the robots. A robot's knowledge represents that robot's perception of the state of the task environment and is often referred to as that robot's world model. Information exchanged during robot communication is clearly derived from the participants' world models. The world model of a robot must represent the objects of the environment and the couplings between those objects which can impact the performance of the robot. This is equivalent to saying that each of the objects in the robot's environment which are significant to the robot's mission must be represented by one or more symbols. Likewise, each of the relevant couplings between the objects of the

robot's task environment must also be represented by one or more symbols.

Three types of knowledge which influence a robot's decision processes can be identified: (1) the knowledge of the present state of affairs or REALITY, (2) the knowledge of past related information or EXPERIENCE and (3) the knowledge of future desires or GOALS. In most situations the robot's world model will represent all three of these types of knowledge in some form.

REALITY is a representation of the robots' environment in its current state. This includes the present state of all of the sensed objects as well as the immediate histories of the states of those objects. The immediate past history is required to completely fonmulate the objects' present states (all of which may not be instantaneously discernable to the robot). EXPERIENCE allows the robot to predict the states of specific objects without recent complete and detailed knowledge of the object's activity through reference to similar encounters with similar objects in the distant (i.e., not immediate) past. The final type of knowledge which is required in the world model is that of GOALS. GOALS represent those states or sequences of states which are approached and avoided by the robots.

The robot functions within a context of a layered model of the world it inhabits. The bottom layer of this hierarchy is intimately associated with the robot's sensors and effectors. Higher layers represent succeeding abstractions of this fundamental level. At each level of the robot's world model there exist entities (location, objectness, etc) in which the model expresses the state of affairs surrounding the robot.

In addition, the robot contains goals at each level, expressed in terms of the entities that make up its world at that level. The behavior of the robot represents changes of effector state which the robot performs in order to realize the hierarchy of goals. Lower goals act as constraints for higher goals, usually merely providing default values for detailed parameters that do not exist at the higher level (are not expressible in terms of the higher level entities). Occasionally, the constraint will be substantive (as in Asimov's laws of robotics). There is no requirement that the transcription of goals from one level down to the next be in any sense optimal; it must, however, be adequate to satisfy the goals at the higher level.

This process proceeds until the level of effector control is reached, and action results. As time proceeds, sensor data is fed back up this chain of levels and integrated effector control results. This whole process can involve simple algorithmic calculation and/or more sophisticated heuristic techniques; the nature of the processing is not important. The layered structure of the world model serves to structure the behavior of the robot.

Three contexts can be distinguished in a communicating robot's world model: (1) SELF, (2) SYSTEM and (3) SURROUNDINGS. The context of SELF is defined by the physical boundaries of the individual robot. This context represents all of the required internal information of the robot. The SYSTEM context is much like that of SELF but includes other cooperating robots as well. If noncommunicating robots complicate the environment then they are represented as components of the SURROUNDINGS. The SYSTEM context is limited to those devices which can communicate or can be communicated to or both. The SURROUNDINGS context represents all of those objects in the environment which are not defined by the robot system. The robot system expects no cooperation from the objects of the SURROUNDINGS. Generally, the SURROUNDINGS represent the primary objects of the task environment. Each of these contexts is represented in the world model by the three types of knowledge which are discussed above.

Communicated Knowledge

There are several reasons for facilitating information exchange between robots. The task environment may require capabilities which exceed the capabilities of the individual robots alone. In this situation information is exchanged to permit coordination of the individual resources to achieve the task. Alternatively, information may be exchanged to allow each robot to validate of its own model of the task environment (i.e., its world model) and the actions which are required to achieve task completion. In this situation, redundant information is exchanged to decrease the effects of errors upon the outcome of any actions. The degree of information exchange is dependent upon the nature of the task domain.

Cooperating robots may have similar or completely different capabilities depending upon the demands of the task. Resource coordination is possible when the devices in the cooperating group have sensor or effector domains that are not identical. Sensor information can be exchanged to permit each robot to have a more complete sensory picture of the task environment than is available through its own sensors alone. Similarly, effector information is exchanged to coordinate the combined efforts of the cooperating robots and enable the robot team to accomplish tasks which are far beyond the effector capabilities of the individual robots.

Situations can arise in which the perceptions and/or actions of single robots may be faulty. These occur either when the task is very noisy or when there exists unresolvable coupling between the robot systems and the environment. In these cases the reliability of the robots' performance can be significantly improved through the exchange of information to permit each individual robot to validate the accuracy of either its own world model or its decisions of action. When information exchange is used for mutual validation the information which is exchanged is redundant with the information gained directly through the individual robots' sensors or with the information used to drive the individual robots' effectors. This implies that the communicated information could theoretically be derived from a single robot's own resources if the task noise can be characterized. In this case, multiple robots are applied to insure that the proper action is taken to insure the achievement of the mission.

Communication between two robots occurs at one or more levels which must obviously be common to the world models of the two devices. The information transferred can be positive, concerning the state of affairs, or normative, setting goals. The lower limit of this layered communications concept is exchanging sensor and effector information directly. This corresponds to a simple teleoperator. Generally goal-setting communication between two robots will be initiated at the highest level they share, and will migrate downward as the two devices cooperate in the shared activity.

In general, any communication will occur at the highest level that serves the need, so as to minimize total communication bandwidth requirements. However, higher level communications require that the participants possess an increased amount of knowledge in common [4]. Many questions remain unanswered regarding the coupling between the level of communications and the concomitant message complexity.

A final consideration of the type of information which is communicated between autonomous entities is consideration of the types of interactions which occur in situations where these entities are cooperating. These interactions can be described by an iterative sequence of phases. These phases consist of:

(1) establish or confirm internal organization of group

(2) establish or confirm common perception of pending task environment

(3) subdivide the current task environment into subtasks and assign subtasks to subgroups

(4) establish or confirm interface commonalities between subgroups

(5) repeat (1) for each subgroup or perform effector action to alter the environment

These phases are not necessarily part of every group of cooperating robots' negotiation procedures. In many cases (1) through (3) may be predetermined before the robots are exposed to the task. However, these phases will occur in any system which must confront task

environments which are incompletely characterized. Incomplete initial task characterization requires the robots to successfully deal with unexpected task components. This common problem in robots is related to that of devising a robot to challenge an unstructured task environment (i.e., one for which there is little a priori knowledge). It is therefore not surprising that the phases of robot interaction parallel the procedures applied in automatic problem solving.

Communications Environment

To this point we have not discussed the communications mechanisms which allow robots to interact. When people use linguistic communications, spoken or written, a context for communication is set up by facing one another and establishing eye contact (face to face), or by saying "hello" and identifying each other (telephone), or by providing a signature and perhaps a return address (letter).

The corresponding activity in computer networking is the establishment of a virtual circuit, which is a structure for the regulated error-free (practically) transmission of information from a transmitter to a receiver whose identities are known to each other. In addition to reliably delivering the data, this scheme allows the transmitter to rely on the fact that the receiver has indeed received the message (by positive acknowledgement or otherwise). Many computer networks can also provide a datagram mode of service in which succeeding packets of information are unrelated as far as the communications transport mechanism is concerned. However, it is the virtual circuit which is analogous to sustained human interaction.

It seems reasonable that robot communications should occur over virtual circuits and that this is a good point of correspondence with networking. The development of a set of agreed upon mechanisms for establishing, maintaining, and disestablishing virtual circuits essentially provides a transport layer. Substantive data (higher level) is communicated within the framework of (one or more) virtual circuits.

Recent advances in communications engineering, particularly in the specific field of computer communications, have made a number of options available to provide the connectivity required to facilitate robot cooperation. The form of the low level transport protocols will be totally dependent on what physical mechanism is employed, but the interface to the higher level protocols will be unaffected. Here are several possible physical communications mechanisms:

A virtual circuit can be realized as a physical link. This will be a very common method of communicating with the "master", of course. It is important to place the physical link in the context of being just one possible realization of a virtual circuit.

Local networking techniques will be very cost effective in many applications, providing flexible high bandwidth communications between large numbers of devices. Many new systems are now appearing in the marketplace (e.g., Ethernet, Net/One, Z-Net), and their impact on robotics will parallel their impact on business/industry in general. The requirements of mobile robots may stimulate the development of local networks using such transmission media as packet radio or infrared broadcast from ceiling "satellites". Regardless of the medium, the local network will provide some well defined interface at the virtual circuit or datagram level.

Over longer distances, the communications resources of private or public data networks may be used. Fortunately, integrated circuits that handle much of the implementation of the commonly used X.25 interface protocol are becoming available.

While detailed examination of these and other various modes of communications is not necessary in this discussion, a brief consideration of the factors which influence robot communications (as well as communication between other entities) provides useful perspective for further discussion about protocols. This discussion of the communications environment will be restricted to consideration of a few particular factors which directly influence the communications between robots. These factors are:

(1) Information Density. The term information density is used to designate a measure of the preprocessing which is required in the transmitting robot to reduce the exchanged information to a bandwidth which is supported by the channel, and in the receiving robot to reconstruct the original data (see channel bandwidth and reliability). If a channel of limited bandwidth is used then the processing burden upon each of the robots is increased. As a result the issues associated with communicated information density involve a tradeoff between communications loading (in terms of bits/second) and processing loading (in terms of instructions/second). The channel can thus be characterized in terms of the number of instructions available/required per bit transmitted/received.

(2) Channel Bandwidth. The bandwidth of a communications channel determines the total communications throughput which can be achieved. This factor is determined by the specific communications scheme, the characteristics of the equipment supporting the link, and the effects of environmental conditions upon the channel properties.

(3) Channel Security and Detection. The security of a channel is the probability that an unintended recipient will intercept and correctly interpret the information content of the communications which are exchanged through that channel. In some cases the mere detection of communications activities by unprivileged parties is undesirable. This is an issue which has received a great deal of attention in the field of computer communications but has not yet been considered in a robot communications context.

(4) Channel Reliability. Channel reliability dramatically affects the protocols chosen for robot communications (especially the data transport layers). This factor is a function of channel noise and is expressed as the ratio of the bits which are received error free to the total number of transmitted bits.

(5) Channel Efficiency. The efficiency of a communications channel is determined by the ratio of the total number of bits exchanged in a communication to the total power required to insure successful receipt of the message. This characteristic can be used to determine the effective bandwidth of a communications channel when the participating robots must be energy self sufficient and, thus, conscious of the issues of energy management. Examples of such situations would be robots functioning in space or deep ocean.

(6) Channel Traffic. The volume of communications traffic competing for a channel dramatically affects the apparent bandwidth of that channel. As a result, transport protocols are often dependent upon the measured or anticipated traffic of a channel (i.e., usually for flow control purposes). In addition, there may be cases when the robots themselves may need to be aware of the degree of channel loading which is present in a communications medium. Such an awareness could be used for traffic flow control (i.e., reduced communications output until the traffic is below a certain level).

IV. RESULTS

PROTOCOLS

The robot communications protocols proposed here consist of two major sets of protocol layers, the communications transport layers and the message content layers. The transport layers provide a reasonably reliable link between sender and receiver over which symbols are exchanged. The content layers format the information that is to be communicated. The separation of transport and content layers is a common technique in computer networking [11] and can be accommodated through protocol nesting [12]. This approach allows communications system design questions to be answered separately from robot processing design questions. As a result, only an unusual communications mechanism or extreme communications mechanism complexity would require the development of new protocols to provide transport layer functions.

Transport Layers

The transport layers are completely independent of the information represented by the content layer. As a result, the data transport aspect of robot communications may be treated as an instance of the more general situation of intercomputer communications. Thus the independence of the transport layers implies that some of the issues which are related to channel reliability and security may be ignored in considering robot communications. Channel reliability may be accomplished through standard flow control techniques and error detection and correction (EDAC) codes. Channel security may be enhanced through the application of any of a number of encryption algorithms and key distribution systems. These channel reliability and security mechanisms will be provided in the transport layers. However, there are special cases where the Issues of channel reliability and security must be considered in higher level protocols.

Content Layers

The content layers of robot communications protocols consist of a layer which is independent of the specific robot task domain and other layers which are strongly task dependent. The task independent layer is rigidly structured and conveys the values of a relatively small number of parameters representing those aspects of the communicated information which are independent of the specific task environment. The task dependent layers must have a flexible structure which can represent the wide variety of information highly dependent upon the particular task environment. The current discussion focuses on the task independent layer and on the elementary tools required to support the development of the task dependent layers.

TASK INDEPENDENT. The task independent content layer consists of three components, the ADDRESS description, the CONTEXT description and the MESSAGE STATE description. The ADDRESS description provides information concerning the identities of the participants in the information exchange process. The CONTEXT provides a structure into which individua1 messages fit as parts. This description uniquely identifies the message within the complete information exchange between cooperating robots as well as linking that message to other messages which relate to the same topic. The MESSAGE STATE describes various properties of the task dependent component of the message and of the message sender's state. This component provides a mechanism to reduce the computational burden of the message processing.

The task independent descriptions of a message represent many properties of the content of the messages in a concise fashion. Flexibility has been traded for efficiency of representation in this component of the message content. As a result, the processing of message content can be simplified. If messages are parsed upon receipt then the task independent component can be used to provide information to facilitate the parsing of the task dependent component (i.e., the higher level layers of the protocols). This structure adds a great deal of flexibility both to the type of input processing which can be done with reasonable ease and to the message format itself.

ADDRESS Description. The ADDRESS description identifies the critical actors to which the task dependent information presented in the message relates. The most common parameter in this description is the sender's identification. In most cases this may be the only parameter which is associated with this description. Further, if the transport layer contains the sender's identification (as is the case with most network virtual circuit transport protocols) then this instance of that parameter may be used instead of supplying it explicitly in the content layers. In complicated situations the ADDRESS may also include identification of those who receive the message for action and for information. Further, other ADDRESS related parameters may be added as demanded by the task environment.

CONTEXT Description. Sacerdoti suggests the use of special parameters to represent such characteristics of communication as shift of focus and cues to data validity [4]. This concept has been expanded in the CONTEXT description parameters. A continuous stream of exchange or conversation between autonomous devices for some interval of time can be represented as a set of interrelated topics with each topic composed of a set of contributing messages. A topic can be identified uniquely by the topic originator identification and a topic identifier which has been assigned by the originator. The only restriction on the selection of topic identifiers is that no originator assign the same identifier to any two topics.

The component messages of a topic may be identified uniquely in any number of ways. For simple situations sequential numbering will suffice. For more complex cases a message originator identification could be added. This parameter is already represented by the sender's identification in either the address description or the transport layers and thus provides capability at little or no expense. A potentially more useful but more expensive scheme for message identification would include a message originator and a timestamp from the originator. The application of timestamps to messages exchanged between distributed databases has been discussed extensively [13-15]. For

special situations the CONTEXT representation could be enhanced further by adding variables to further link topics or messages together. The messages of a topic could be viewed as elements of a database and be linked according to the organization required by the task.

In its simplest form, the CONTEXT description provides an indication of the change of conversational focus as well as some data validity check (e.g., out of range arguments or inconsistent topical changes). The addition of timestamps to messages adds the dimension of message phase as well as accommodating distributed database issues.

A virtual circuit mechanism implemented in the transport layers provides resources that serve important functions in establishing several task independent properties of robotic communication. The source and destination identifiers of the virtual circuit can identify not only the physical robotic entities communicating, but can also provide context description by establishing to which topic a given message belongs. This is analogous to the "socket" concept of the ARPANET. New virtual circuits are established as new topics are "discussed", and the virtual circuit mechanism does the bookkeeping. Predefined socket numbers known to all robots aid in the initiation of communications and provide standard services. However, for those communications schemes which do not support a virtual circuit mechanism in the transport layers then parameters in the ADDRESS and CONTEXT descriptions of the task independent layer would have to be employed.

MESSAGE STATE Description. MESSAGE STATE variables describe some isolated properties of the task dependent component of the message. One of these variables indicates whether the message is a question or a statement. Another indicates whether the message sender's interpretation of the message topic state is positive or negative (i.e., converging on or diverging from the related set of goals, respectively). The tense of the message could also be represented by a MESSAGE STATE variable to convey the temporal significance of the information. These three state variables can be represented by a small number of bits and thus can together compose a single state word.

Another state variable is a measure of the urgency or priority of the message content. This measure could be an integer value which indicates the immediacy of the information. The value of this variable could be used to hasten message processing for messages which require special or immediate attention early in the receiving process. Some communications schemes allow the indication of message priority in the transport layers which is used by the communications controller for flow control. However, the measure of message priority in the transport layers may or may not be able to perform the role of message urgency. In those cases where the

transport features may not be used in this role (e.g., when the message content is encrypted or when the flow control mechanism is independent of the message urgency) then the urgency parameter is required in the MESSAGE STATE description.

The four MESSAGE STATE variables which are presented above do not represent a complete set of possible state variables for messages. Other variables could be devised to represent often used responses in a concise manner. Some other possible applications of MESSAGE STATE variables include the indication of a requirement for overt response or the indication of a requirement for a return message or acknowledgement [4].

TASK DEPENDENT. The topic dependent layers of the content of a message provide information inextricably coupled to the task description. The high level structure of this component is derived from a model of the task environment. Detailed examination of the layers which compose the task dependent portion of communications is deferred as the subject of another discussion [16]. Nevertheless, some general features of these layers are introduced below.

The task dependent layers represent all of the meaning contained in the message content which is above the task independent layer. These layers are divided into numerous virtual circuits according to the various topics which are being communicated. These layers will undoubtedly be represented by some level of symbology (e.g., ASCII symbols, words, sentences). However, construction of the initial components of the task dependent layers should be approached from a direction which is as free from dependence on specific symbology and form as possible. This sort of freedom provides the flexibility that is required of a set of generalized protocols to support robot communications.

Design of the task dependent layers of robot communications protocols involves two classes of decisions. One class determines those fundamental factors of the protocol layers which are required for successful performance in the task environment. This class of decisions includes choices of the types of information which are represented at the various levels, the definition of the minimum representations required by the task environment and the interactions which exist between the higher layers. The other class of design decisions consists of those factors which can be determined irrespective of the fundamental considerations. Included are choices of representing symbology, particular format of representation and the identification of such convenient constructions as pronouns, quantifiers and expletives. This class of decisions requires consideration of those factors which are not directly related to the communications processes themselves. Most decisions of this class impact such minor issues as overall flexibility, reliability and utilization.

The message format resulting from the above considerations is:

   [communication header (task independent component) (task dependent component) communication trailer]

where

   communications header = <transport mechanism dependent information (e.g., addressing, routing)>

   task independent component = <address description, context description, message state description>

   communications trailer = <transport mechanism dependent information (e.g., checksum)>

and

   address description = <sender identification>

   context description = <topic originator, topic identifier, message originator, message timestamp>

   message state description = <inflection, interpretation, tense, urgency>

The form which is presented above is intended as only one layer above the transport layer. This layer is independent of the task environment in which the cooperating robots function. The layers of protocols which are above the task independent layer are considerably more entwined with the robots' particular representation of the task environment than the lower layers.

ENVIRONMENTAL EFFECTS

Communications Environment

Six communications environment factors were discussed above: information density, bandwidth, security, reliability, efficiency and traffic. Naturally, these factors affect communications protocols. The conditions of restricted bandwidth and adverse efficiency force economy of communicated data thus demanding more efficient protocols (i.e., higher entropy) in the transport and content layers. The content layers can be made more efficient by increasing the density of the information carried. This can be accomplished by using more efficient symbology in the task dependent layers and by transferring more of the content burden to the task independent layer which is more efficient but much less flexible representation.

Channel security and reliability factors place an additional burden upon the transport layers and the task dependent layers. In most cases increased security or reliability considerations can be handled

entirely in the transport layers (e.g., encryption and EDAC encoding). However, these factors of the communications environment have implications on the patterns of robot interaction and thus influence the type of information which is communicated. As a result, the task dependent layers can also be affected. Similarly, special considerations of the communications traffic situation can be handled in the transport layers exclusively (i.e., flow control). However, the conditions which cause these special traffic situations are part of the task environment and thus influence the content of the task dependent layers.

Task Environment

Seven factors of the task environment which influence robot communications have been identified. These factors are task dynamics, initial knowledge state, task and goal complexity, task and goal coupling and world model commonality. Task dynamics reflects the rates at which objects of the task environment change state. The initial knowledge state is the state of the robots' collective world models at the beginning of the mission. Task complexity and goal complexity characterize the number of objects and goals which are associated with the task environment, respectively. Object coupling describes the degree to which the objects of the task environment are coupled to one another. The factor of goal coupling is the degree to which the goal structures of the system are interrelated. The factor of world model commonality is the amount of overlap that exists between the world models of the cooperating robots.

Task dynamics determines the time available for a robot to respond correctly to relevant sensed stimuli. As a result, this factor affects the amount and type of processing that can be performed to integrate the stimuli with the action. Since communications processing is but one part of the required processing between events, task dynamics affects the transport and content layers just as a condition of limited channel bandwidth would. However, this is the only factor of the task environment (aside from communications effects) which affects the transport layers.

Task and goal complexity add objects to the task environment and thus influence the task dependent layers. Similarly, the factors of task and goal coupling add objects to the task environment and thus place additional burden on the task dependent layers. The initial state of knowledge determines a considerable portion of the task as well as the information which must be exchanged between the cooperating robots. The initial knowledge state of each robot determines the subset of those robots' world models which can only be established via communications. World model commonality determines the symbols which are exchanged and thus affects the composition of the task dependent layers. It should be

noted that some world model commonality must exist for communications to be possible at all.

The effects of these factors on the task dependent layers are limited to the required symbology. Care has been taken to avoid contamination of the independent layer by the factors inherent to the task. There are cases when this layer offers a vehicle for improving the efficiency of the protocols. This could be especially true for situations where the task and goal complexity are high (i.e., task environment with large numbers of objects) by representing common states of the task environment in this layer. The MESSAGE STATE parameter of interpretation does this to a small degree. However, clear separation of the functions of the task independent and task dependent layers offers a conceptual advantage and should be preserved when processing and communications limitations permit.

V. CONCLUSIONS

Robot communications is an expansive topic. Space limitations have precluded exploration of many of the pertinent issues here, and have necessitated a more superficial treatment of the areas which have been addressed. Nevertheless, a foundation has been established for the development of robot communications protocols. The structure presented here makes a clear distinction between the transport and content layers, serving to decouple the details of the robotic interaction from the implementation of the data communications. This allows robot designers the freedom to exploit the transport protocols developed for a wide variety of computer communications situations.

The theoretical foundation of robot communications presented here provides enough detail to permit a formulation of the lowest (e.g., task independent) content layer. This layer conveys basic information about the communications situation: the originator's state, message content context, and type of information. However, most communications situations will require higher content layers to represent task dependent information.

The concepts presented herein provide a starting point for the development of these higher task dependent layers. These concepts include basic models for both single robots and cooperating groups as well as sketches of robot world models and domains of communicated knowledge. All of these concepts contribute to the development of what might be termed an "omniscient" perspective of robot communications. The approximation of such a perspective is necessary for further development of protocols for robot communications.

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