Casualty Modeling for Real-Time Medical Training*

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Abstract

We present a model for simulating casualties in virtual environments for real-time medical training. It allows a user to choose diagnostic and therapeutic actions to carry out on a simulated casualty who will manifest appropriate physiological, behavioral, and physical responses. Currently, the user or a "stealth instructor" can specify one or more injuries that the casualty has sustained. The model responds by continuously determining the state of the casualty, responding appropriately to medical assessment and treatment procedures. So far, we have modeled four medical conditions and over twenty procedures. The model has been designed to handle the addition of other injuries and medical procedures.

Keywords: Casualty models, patient simulation, medical procedures, computer simulation, virtual environments.

1 Introduction

Advances in computer graphics, improvements in hardware performance, and the growing number of natural interaction techniques are increasing the practicality of using computers for medical training applications. While optimal training comes from attending to real patients, it is less risky to make use of actors portraying appropriate injuries and behavioral responses. But the high cost of actors, their inability to portray all the physiological manifestations of injury, and the need to give many students sufficient training means that in many situations, simulated patients in virtual environments can provide a useful and effective substitute.

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In patient simulation, there is often a tradeoff between realism and the accessibility of the training tool. On one end of the spectrum, patient mannequins such as the CAE LinkMed®Patient Simulator [6] provide extremely realistic, "hands-on" training with actual medical equipment. However, using it requires the resources of an actual operating room. On the other end of the spectrum, text- or menu-based PC simulations [1] are easily accessible from desktop computers or even portable laptops but provide limited situational realism. We present a model that falls in between these two extremes–a virtual environment simulation that requires specialized interaction equipment, but equipment that is becoming more widely available, even for clinical use.

We have focused on training medical corpsmen in virtual battlefield conditions, but our model is intended to be extensible to civilian emergency medical training. Simulating human casualties requires an underlying physiological model that is medically sound. Simulated casualties must respond to medical assessment and treatment procedures, whether or not those procedures are appropriate to the patient's conditions. Furthermore, the casualties must display physical and behavioral manifestations of injury that are realistic enough to prompt appropriate medical attention. In this paper, we examine the problem of creating realistic, real-time simulations of human casualties for use in virtual environments.

2 Casualty Model

Our model demonstrates the feasibility of integrating physiological state into an interactive animation. We designed and implemented our model in such a way that a casualty's condition over time follows from the type of injuries he has sustained and the medical interventions performed on him (if any). We currently model the following conditions that can result from penetrating wounds to the chest and/or abdomen: tension pneumothorax, hemothorax, pericardial tamponade, and abdominal bleeding. A casualty may manifest one or more of these conditions. The current treatments available include performing a needle aspiration, administering fluids, and applying an occlusive dressing on a wound.

A casualty's state is then linked with various visual effects to imitate the appearance and behavior of real casualties. Our current model uses a simplified physiological model and a large, but incomplete, set of graphical effects. The model is currently being modified to use a more detailed physiological model. It is easily extensible to include additional visual effects. Concurrent research is being done to create wound appearances and motor behavior with the goal of simulating casualties who are realistic enough to elicit appropriate diagnostic and therapeutic behavior from the medical corpsman trainee (Section 2.4).

2.1 Simulating Casualty State

Over the years, researchers in trauma care have developed various methods for estimating the severity of a patient's injuries. One method widely used by emergency medical personnel and endorsed by the American Trauma Society is the Trauma Score [8] (Fig. 1). It reflects basic assessments of the respiratory and circulatory systems, and incorporates the Glasgow Coma Score which represents a casualty's neurological state. These rankings are combined to yield

Respiratory Rate	10-24/min	4	**Glasgow Coma Scale**		
	24-35/min	3	**Eye Opening**	Spontaneous	4
	36/min or greater	2		To Voice	3
	1-9/min	1		To Pain	2
	None	0		None	1
Respiratory Expansion	Normal	1	**Verbal Response**	Oriented	5
	Retractive	0		Confused	4
Systolic Blood Pressure	90 mmHg or greater	4		Inappropriate Words	3
	70-89 mmHg	3		Incomprehensive Words	2
	50-69 mmHg	2		None	1
	0-49 mmHg	1	**Motor Response**	Obeys Commands	6
	No Pulse	0		Localized Pain	5
Capillary Refill	Normal	2		Withdraw Pain	4
	Delayed	1		Flexion (pain)	3
	None	0		Extension (pain)	2
				None	1

Figure 1: Trauma Scale

a single Trauma Score, such that a higher score indicates a greater likelihood of survival. As a first approximation, we are using a casualty's Trauma Score values to define his/her physiological state at any given time in the simulation. The Trauma Score was selected as the basis of our casualty model for its comprehensive nature and since it has proven to be an accurate and reliable predictor of a trauma patient's condition.

As part of its output, our simulation can display a plot of a casualty's assessment parameters over time. The plotted values reflect the type of injury, the manifested medical conditions, and any medical intervention invoked by the corpsman trainee. The simulation is also manifested in a 3D *Jack*®human figure (Fig. 2) that represents the casualty and looks and behaves in accordance with its Trauma Score values at any give time. A trainee may determine the state of the casualty through visual examination or by probing the casualty (currently, through a menu-driven interface). The system responds with a written, visual, or audio response. As in realistic emergency medical situations, the trainee may ask the casualty questions to assess the situation. There are also several commands corresponding to treatment procedures, which when invoked, generate appropriate changes in the state of the casualty. Fig. 3 lists the user commands available in the current casualty simulation and their corresponding response types. The simulation also displays additional visual injury manifestations, including distended neck veins, cyanosis, chest movements, and general thrashing of the extremities.

This system is a first step towards enabling a medical corpsman to train through treating a simulated casualty. Currently, the system allows a trainee to select from a menu any of a set of predefined diagnostic and therapeutic procedures which an animated corpsman then carries out on a simulated casualty. The underlying structure of the system supports future

Figure 2: *Jack* Casualty in Battlefield Environment

extension to a virtual medical corpsman in a virtual environment controlled by a trainee corpsman. There are two ways of augmenting the virtual battlefield with such a medic. In one method, the trainee corpsman issues commands to a simulated medical corpsman who carries out the specified procedures. The trainee controls the simulated medic either with textual input, menu selection, or verbal commands. In the second method, the trainee uses virtual environment tools to control an "avatar" whose behavior reflects the trainee's physical movements. Note that the ambiguity of such movements requires the addition of spoken or textual descriptions of the procedures being performed (e.g. "I am applying pressure to the sternum.") Since the current system accepts textual input and menu-based commands corresponding to medic trainee actions, it supports both augmented interaction methods.

2.2 Implementation

We model the casualty using a package for creating and running communicating parallel state-machines, which we call Parallel Transition Networks (PaT-Nets) [2, 4]. These state machines have been used to control the sequencing and timing in animations to implement behaviors as low-level as grasping [4] and as high-level as playing the game hide-and-seek [15] and carrying on conversations [7].

We implemented the casualty model using PaT-Nets, because the state of a casualty characterized in terms of Trauma Score rankings is naturally represented by states in a state machine. Also, PaT-Nets are good at sequencing actions based on conditions in the environment such as the passage of time. Since injuries and treatments are modeled by the time-based, physiological changes that they generate, PaT-Nets provide a reasonable computational model.

We currently use four types of Parallel Transition Networks in defining a casualty model:

DIAGNOSTIC COMMANDS		
Assessment Parameter	**User Command**	**Response Type**
Respiratory Rate	`query-RR`	numeric display
Respiratory Expansion	–	animated display
Blood Pressure	`query-BP`	numeric display
Capillary Refill	`take-CR`	visual
Eye Opening	`open-your-eyes`	visual
	`apply-sternal-pressure`	visual
Verbal Response	`name?`	written, audio
	`I.D.?`	written, audio
Motor Response	`move-your-foot`	visual
	`squeeze-my-hand`	visual
	`apply-sternal-pressure`	visual
SITUATION ASSESSMENT COMMANDS		
	`are-you-ok?`	written, audio
	`what-happened?`	written, audio
	`do-you-have-pain?`	written, audio
	`where-does-it-hurt?`	written, audio
THERAPEUTIC COMMANDS		
	`needle-aspiration`	state changes
	`give-fluids`	state changes
	`occlusive-dressing`	state changes

Figure 3: User Commands

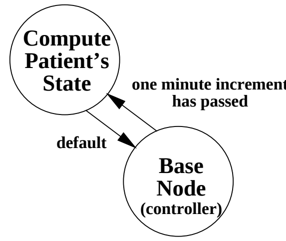

Figure 4: Controller PaT-Net

- A *Controller network* that receives messages regarding the Trauma Score assessment parameters and computes the current casualty state on a minute- to-minute basis,
- *Injury networks* that specify the physiological changes resulting from specific medical conditions and send appropriate messages to the controller network,
- *Treatment networks* that specify the physiological changes resulting from administered treatments and send appropriate messages to the controller network, and
- *Assessment parameter display networks* which generate the visual effects of changes in Trauma Score rankings and respond to user input.

2.2.1 Controller Network

The controller network shown in Fig. 4 receives messages from the injury and treatment networks, specifying how the given injuries and any procedures that have been performed by the corpsman are affecting the casualty at the current time. In its base node, the controller receives messages and spawns PaT-Nets when the corresponding treatments are administered. Each minute, the controller network transitions to its computation node. In this node, the controller looks at the current messages and computes the casualty's current state. It then sets the values for each of the casualty's assessment parameters, making sure that the values remain in their valid ranges.

The controller network is able to consider combinations of injuries and treatments and determine what effects (if any) the administered treatments have on the casualty's injuries. Fig. 5 shows the pseudocode for a simplified version of the base node of the controller network. If the administered treatments have an immediate and complete therapeutic effect on the given injury, the controller exits the PaT-Net corresponding to the injury. However, if the effect is cumulative over time or does not completely relieve the effects of the injury, the injury PaT-Net continues to send messages to the controller. For instance, since a needle aspiration completely reverses the effects of tension pneumothorax, the controller exits the corresponding tension pneumothorax PaT-Net when a needle aspiration PaT-Net is spawned. On the other hand, when fluids are given to a casualty with abdominal bleeding, the corresponding PaT-Net remains in existence, to model the effect of the fluids diminishing over time.

Since the controller network considers messages from all injuries and treatment networks and ultimately controls the casualty's current state, the model can be easily extended with

```
(DEFACTION :base-node-action
      (if (and received-needle-aspiration has-tension-pneumothorax)
            (progn (exit tp-patnet) (spawn na-patnet)))
      (if (and received-fluids has-abdominal-bleeding)
            (spawn fluids-patnet))
      (if (and received-fluids has-pericardial-tamponade)
            (spawn fluids-patnet))
      (if (and received-fluids has-hemothorax)
            (spawn fluids-patnet))
      (if (receive-assess-param-msg)
            (add msg to msgQueue)))
```

Figure 5: Controller Base Node Pseudocode

new injuries and new treatments. The changes required for new networks are encapsulated in the controller PaT-Net.

2.2.2 Injury and Treatment Networks

Medical conditions that result from injuries sustained and/or treatments administered are modeled as individual PaT-Nets. These networks specify changes in the Trauma Score assessment parameters, given the time of injury or treatment administration. The injury networks represent the deterioration in the casualty's condition over time. The treatment networks represent potential improvements in the assessment parameters due to the treatment. Incorrect treatment procedures may not lead to improvements in the patient s state. At appropriate times, the active injury and treatment networks send messages to the controller network regarding the values of the assessment parameters. The controller network considers both the casualty's injuries and administered treatments in determining the effect of treatments. Since treatments may have different effects depending on patient state, the controller may ignore certain messages. For instance, a needle aspiration on a casualty with tension pneumothorax will lead to a marked improvement in state; however, it will have little effect on a casualty with a hemothorax. Thus, in the hemothorax case, messages from the needle aspiration PaT-Net are ignored.

Currently, the modeled medical conditions include tension pneumothorax, hemothorax, pericardial tamponade, and abdominal bleeding. A single wound may lead to one or more injuries. For instance, a penetrating abdominal wound may result in hemothorax, pericardial tamponade, and abdominal bleeding (as well as a lacerated diaphragm, currently not modeled). When multiple injuries are sustained, we currently use the lowest value of each Trauma Score value as the overall value, assuming that the worst effect is most influential but that combined effects are not additive. The modeled treatment networks include performing a needle aspiration, giving fluids, and applying an occlusive dressing to a wound. Fig. 6

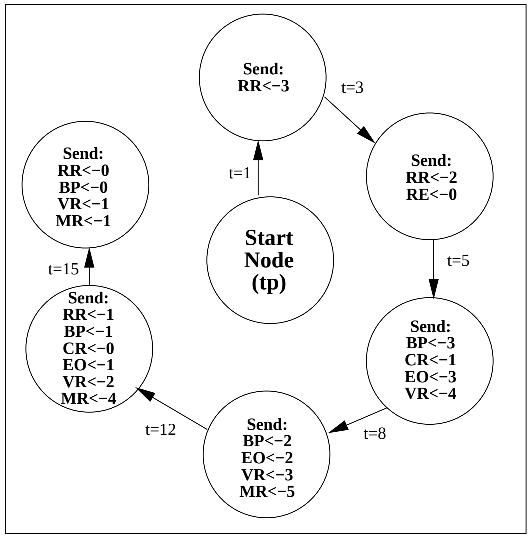

Figure 6: Tension Pneumothorax PaT-Net

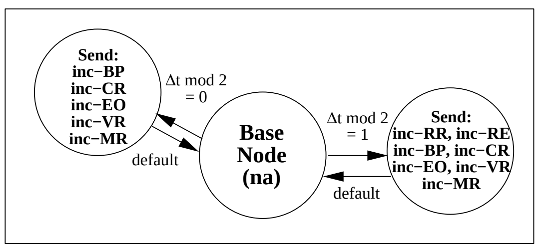

Figure 7: Needle Aspiration PaT-Net

shows a sample injury network, and Fig. 7 shows a sample treatment network. The networks are described in more detail in the example below. The time course of each condition (with and without treatment) reflects the experiences of one of the authors (Clarke) who has participated in over 5000 trauma responses. When the system is updated to include a more detailed physiological model, these networks will be modified accordingly to take advantage of the improved model.

2.2.3 Assessment Parameter Display Networks

Each modeled assessment parameter has a network containing methods to produce appropriate physical, behavioral, verbal, and numeric responses to user commands reflecting the casualty's current state. The modeled assessment parameters are those used in the Trauma Score: respiratory rate, respiratory expansion, systolic blood pressure, capillary refill, eye opening verbal response, and motor response. The accepted queries and output types are shown above in Fig. 3.

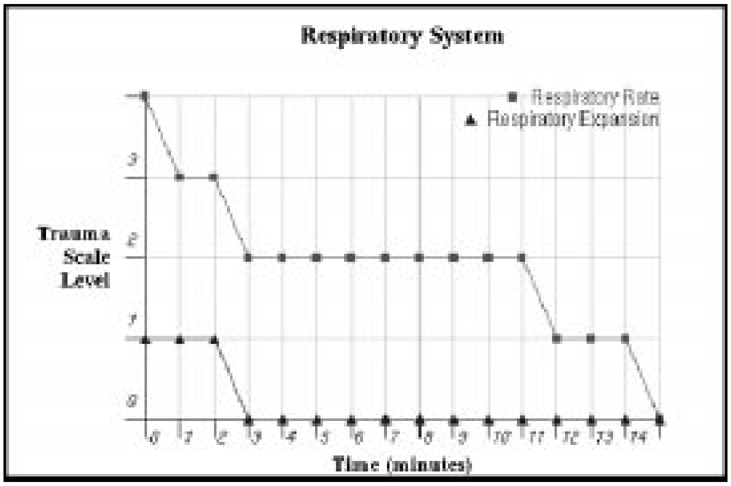

Figure 8: Tension Pneumothorax Plot – No Treatment

2.3 Example: Tension Pneumothorax

Figs. 6 and 7 show the tension pneumothorax and needle aspiration PaT- Nets, respectively. If the casualty receives a tension pneumothorax, the corresponding PaT-Net is spawned, beginning in its start node. At the time of injury, the tension pneumothorax PaT-Net starts its clock. After specific time intervals (1, 3, 5, 8, 12, and 15 minutes), the tension pneumothorax PaT-Net transitions to a new state where it sends messages to the controller network to decrement the appropriate assessment parameters.

When the casualty is given a needle aspiration, the controller network exits the tension pneumothorax PaT-Net since the effect of a needle aspiration is immediate and completely reverses the effects of the tension pneumothorax. The controller then starts a needle aspiration PaT-Net in its base node. At one and two minute intervals, it transitions to a new state and sends messages to increment the appropriate assessment parameter values. Fig. 8 shows the plot of the assessment parameters reflecting the Respiratory System when the casualty develops a tension pneumothorax and receives no treatment. Fig. 9 shows the Respiratory System plot when the casualty receives a needle aspiration 10 minutes after the time of injury. Note the marked improvement in the casualty's condition after the needle aspiration is performed.

2.4 Enhancing Visual Realism

Concurrent research is being done to enhance the visual realism in the casualty's appearance. Two such efforts are (1) creating visually convincing wound simulation, and (2) generating dynamics-based, passive behaviors of casualties who lack conscious control of their bodies.

The simulated appearance of a wound and its changes over time should be realistic enough to invoke the appropriate diagnostic and therapeutic responses from a medic. The simulation of internal and external bleeding can be portrayed using a system for modeling and animating liquid phenomena [10, 11] developed by Foster and Metaxas. Their system

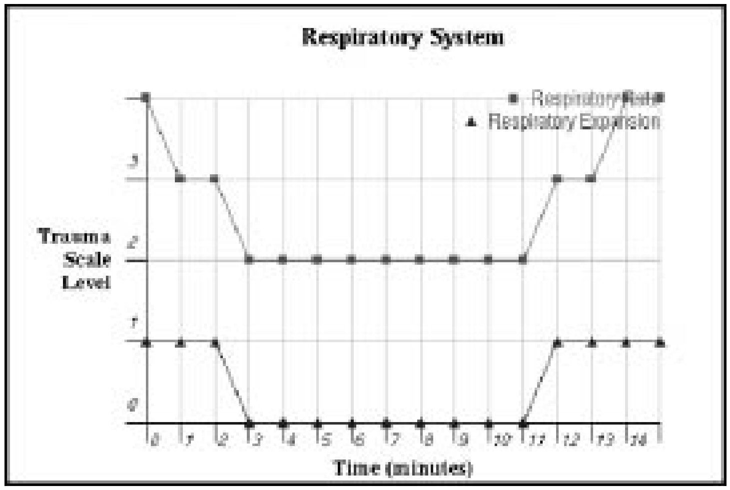

Figure 9: Tension Pneumothorax Plot – Needle Aspiration at 10 minutes

can be used to portray the amount of blood loss and to simulate such phenomena as blood clotting and water bridging.

The animation of active behaviors in Jack involves agents that have control over their motions. However, human casualties may not have complete control over their bodies due to shock, neurological damage, or overwhelming external force and that requires treating their animation differently. For instance, the arm of an unconscious person should fall off the side of a stretcher if it is near the edge and not tied down. Thus, the quality of casualty animations can be enhanced by adding dynamic properties to the casualties in the simulations. Kokkevis' research in dynamic simulation is being used to generate the passive behaviors of our casualties by assigning mass and inertia to the body parts of the injured humans and using a dynamic simulator to generate physically accurate and visually convincing motions [13].

3 Related Work

Simulated animations of casualties have unique requirements that have not been addressed by previous systems for the animation of human figures or other creatures. These systems have used two approaches to natural motion: inverse kinematics [3] and dynamic models [5, 14, 17]. Systems using inverse kinematics are given a specified postural/gestural goal; the systems work backwards to compute a feasible plan to obtain the goal. Previous inverse kinematics systems have focused on motion planning given a goal position or a specified task, ignoring the generation of "involuntary" movements (inherent to casualties) where a specific goal may not be known. Such movements include responses to pain, involuntary behaviors related to physical condition, and movements caused by other agents acting on the body. Dynamics-based systems are given all the forces acting on a body and compute the resulting movements. While it is important to account for external forces acting on the unconscious casualty, not all influences on a casualty can be modeled as dynamic forces. For instance, pain and physiological well-being affect the movements of a casualty but cannot be directly specified as forces. Generating realistic casualty models requires not only a combination of task- oriented motions available using inverse kinematics and involuntary, dynamics-based movements, but also some mechanism for creating motions related to pain and physiological influences.

Some previous work has been done in simulating various autonomic behaviors of human figures. This includes maintaining balance [3], automatic and natural eye following, and appropriate eye blinking [16]. In our casualty model, we extend these to the more complex, autonomic responses to pain and other physiological conditions.

Agent-based animation systems generate behaviors using reactive agents with perception [14, 18, 19] or agents that use a combination of perception and intentions [15, 20]. Like agents, simulated casualties must react to stimuli in the environment; however, the stimuli that affect casualties are dominated by diagnostic and therapeutic procedures performed by medics rather than by environmental obstacles or accessibility of desired objects. With respect to self-motivated behavior, initially we are assuming that the only significant intention of casualties affecting their behavior is to alleviate pain. As such, planned and intentional movements are less important in achieving realism than involuntary physiological effects and responses to performed medical procedures. In our future work, we will investigate integrating intentional and autonomic behavior, allowing casualties to attempt to carry out their regular defensive or offensive maneuvers.

As stated previously, our casualty model lies somewhere between realistic but fairly inaccessible patient mannequin simulators and readily available, text-based PC simulations. When incorporated into a virtual environment, our casualty model provides some visual and physical realism. However, the system requires specialized interaction equipment.

4 Conclusion

We have described and implemented a model that generates human casualty simulations to be used in virtual environment training. Our model generates medically-based physiological, behavioral, and physical changes over time. Further, our model may be enhanced to portray a more realistic appearance of wounds and to capture the passive behaviors of casualties. Our model is easily extensible to include more injury types and treatments, as well as additional visual features of injury.

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