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Mark Rajai, Ph.D.

Editor-in-Chief
California State University-Northridge
College of Engineering and Computer Science
Room: JD 4510
Northridge, CA 91330
Office: (818) 677-5003
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THE INTERNATIONAL JOURNAL OF MODERN ENGINEERING EDITORS

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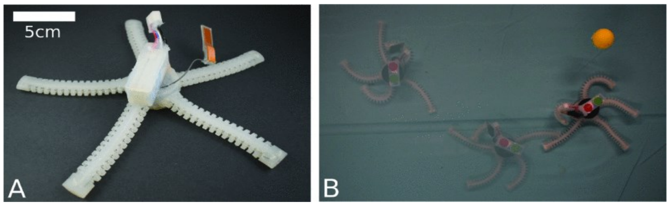
Biomechatronics and Sea Creatures

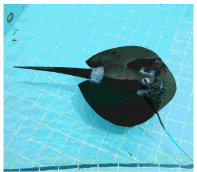
Philip Weinsier, IJME Manuscript Editor

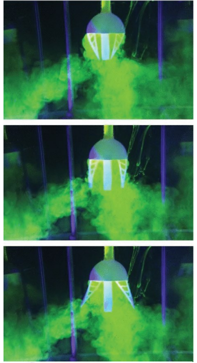
If you are into biomechanical systems, sea creatures, and SpongeBob SquarePants, then continue reading! Of the ever-increasing amount of research that is being done on the exploration of the ocean, much is focused on the development of underwater vehicles, which have many advantages in certain situations. But conventional, propeller-driven engines are outclassed by the swimming performance of fish, in terms of efficiency, noise, and maneuverability.

For example, SpongeBob's sidekick, Patrick Star, is now starring in another role as an untethered biomechanical underwater echinoderm. In this image, he's seen working his way towards his goal, the orange ball.



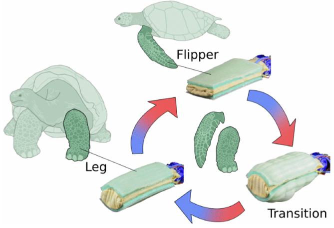
Or, how about this micro-biomimetic manta ray, actuated by shape memory alloy (SMA) wire and created out of ionic exchange polymer metal composites (IPMCs). SMAs are solid smart materials capable of being actuated quietly by electric current and made into myriad shapes. Titanium-nickel alloy (TiNi), aka Nitinol, is one of the most commercially available SMAs and shows its advantages in high recovery stress (>500 MPa)—which is hundreds of times that of the biological muscle—low operational voltage, average operational strain (<8%)—roughly equal to biological muscle—and long life.





But Patrick is not the only sea creature to capture the fascination of researchers. Also shown here is a jellyfish expelling water, mostly in the direction of the tentacles, and a morphing robotic limb turtle that can operate on land or adapt the structure and stiffness of its limbs for amphibious operation. And, its rigid shell provides a convenient, protected space for motors, electronics, and payloads.

Whatever your interest, I encourage you to read the article featured in this issue of IJME on p.16, and peruse the government-funded work provided in the table below.



Robot	Biomimicry	Actuation	Swimming	DOI Reference
Multi-Joint Fish	Carangiform Fish	Electric Actuators (Servomotors)	BCF Undulation	10.1016/S1672-6529(09)60184-0
Biomimetic Fish	Fish	IPMC	BCF/MPF Oscillation	(10.1109/ROBIO.2015.7418776) and (10.1007/s41315-017-0019-5)
SoFi	Fish	FEA (Pneumatic/Hydraulic)	BCF Undulation	(10.1126/scirobotics.aar3449) and (10.1089/soro.2013.0009)
Stingray Robot	Stringray	Electric Actuators (Servomotors)	MPF Undulation	10.1109/ROBIO.2009.5420423
Octopus Arm	Octopus	Motor-Driven Cables	Crawling	10.1088/1748-3182/6/3/036002
Octopus Arm	Octopus	Motor-Driven Cables/SMA Springs	---	10.1163/156855312X626343
Octopus Robot	Octopus	Motor-Driven Cables/SMA	Crawling	10.1088/1748-3190/10/3/035003
Cuttlefish Robot	Cuttlefish	DEA	Jet Propulsion	10.1038/s41598-018-32757-9
Robojelly	Jellyfish	SMA	Propulsion	10.1088/1748-3182/6/3/036004
Octobot	Octopus	FEA (Chemical Reaction)	---	10.1038/nature19100
Morphing Underwater Walker	---	FEA (Hydraulic)	Walking/Crawling	10.1109/LRA.2019.2931263
Jellyfish-Inspired Soft Robot	Jellyfish	DEA	Propulsion	10.3389/frobt.2019.00126
Robotic Manta Ray	Manta Ray	IPMC	MPF Undulation	10.1109/ROBIO.2015.7418776
Micro Biomimetic Manta Ray	Manta Ray	SMA	MPF Undulation	10.1109/ROBIO.2009.5420423
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Starfish-Like Soft Robot	Starfish	SMA	Crawling	10.1016/S1672-6529(14)60053-6
RoboScallop	Scallop	FEA	Jet Propulsion	10.1109/LRA.2019.2897144
Eel-Like Robot	Leptocephalus	Fluid Electrode DEA (FEDEA)	BCF Undulation	10.1126/scirobotics.aat1893
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Soft Underwater Starfish	Starfish	Servo-Driven Tendon Wires	Propulsion	10.1109/LRA.2021.3070305

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AN ANALYTICAL MODEL OF A NEW TYPE OF LEARNING AUTOMATA

Prateek S. Aggarwal, Boston University; Chenhui Liu, Boston University; Lev Levitin, Boston University

Abstract

In this paper, the authors present the novel concept of probabilistically switch-action-on-penalty learning automaton (PSAPPSAPA), which is a fixed-structure stochastic automaton (FSSA) with a fan-shaped state transition diagram, where each branch of the state space is a chain of states associated with a particular action. The first states of all chains form a circle of initial states. The PSAPPSAPA can switch from a present state in any chain to the initial state of the next chain in the circle, probabilistically, on each penalty with some fixed non-zero probability. This action-switching probability is a function of the distance (in the number of states) of the present state from the initial state of its branch. The learning behavior of PSAPPSAPA is determined by the dependence of the action-switching probability on the distance from the initial state. The probabilistic action-switching capability distinguishes PSAPPSAPA from conventional FSSA, where only some states transit to states with a different action. This action-switching capability at any time is also typical for conventional variable-structure stochastic automata (VSSA) except that it comes with added computational complexity.

VSSA are more adaptive than traditional FSSA in non-stationary environments, because of this action-switching capability. The authors believe that the addition of this capability should also make the PSAPPSAPA more adaptive in non-stationary environments than classical FSSA, while preserving the simplified computational complexity of FSSA. In this study, the authors further identified different learning automata within this class that differ in their response to penalties from the environment, and named them ambivalent-PSAPPSAPA, optimistic-PSAPPSAPA, and pessimistic-PSAPPSAPA. The three automata were found to have very different ε-optimality properties. The effectiveness of the proposed framework was demonstrated through the theoretical analysis of optimality of the PSAPPSAPA in stationary environments. The authors believe that the model will be relevant for multiple fields, such as reinforcement learning, mathematical psychology, neuroscience, behavioral science, and mathematical finance.

Introduction

Over the past few decades, the study of learning automata (LA) has taken center-stage in the field of machine learning and computational intelligence (Narendra & Thathachar, 2012; Rezvanian, Saghiri, Vahidipour, Esnaashari & Meybodi, 2018), with early work on learning developed in the context of mathematical psychology (Bush & Mosteller, 1955; Tsetlin, 1962; Atkinson & Bower, 1965; Norman, 1972). Learning is the ability to improve performance using past experience in an unknown environment. The theory of LA provides a framework for such a learning ability.

An LA is a simple entity comprised of multiple states, with at least one of the states being described as current. At each instant in time, an automaton selects one of several available actions, according to action probabilities determined by the current state or states. The environment provides a random response to the action selected; the response is simple and can be either a reward indicating success or a penalty indicating failure (Narendra & Thathachar, 2012). Depending on the environment response, the automaton makes a transition into a new current state. Provided that the reward/penalty from the environment is only weakly related to the action selected, an LA represents a suitable strategy for maximizing the probability of reward over multiple attempts at selecting the best possible action. Throughout the remainder of this paper, each attempt will be referred to as a step in a sequence of attempts. Thus, an LA is an adaptive decision-making device that operates in an unknown stochastic environment and progressively improves its performance via a learning process. Such an LA can form the nucleus of a learning system with much more elaborate logic, with the architecture of the LA handling the random nature of the environment.

Since action selection scenarios are prevalent in various machine learning and real life situations, such as in training deep neural networks (Guo, Li, Qi, Guo & Xu, 2020) and clustering (Hasanzadeh-Mofrad & Rezvanian, 2018), intelligent cloud computing and resource allocations (Oommen & Roberts, 1998), adaptive recommender system and social networks (Ghavipour & Meybodi, 2016), network and filter design (Misra, Chatterjee & Guizani, 2015), optimization of cooperative tasks (Zhang, Wang & Gao, 2021), and queuing systems (Vahidipour & Esnaashari, 2018), theoretical research in this field has acquired further significance in recent years (Economides & Kehagias, 2002). In finance, accurate prediction of bankruptcy is important in mitigating economic loss (Mazhari & Monsef, 2012) and LA can be used for selecting components during financial portfolio optimization (Sbruzzi, Leles & Nascimento, 2018). LA can be applied to a broad range of control problems characterized by nonlinearity and a high degree of uncertainty (Ghaleb & Oommen, 2019; Abeyrathna, Granmo, Zhang, Jiao & Goodwin, 2020). Modeling human learning has also been pursued using LA (Oommen & Hashem, 2010). In this current study, the authors applied the PSAPPSAPA automaton for channel selection by multiple devices in an ad-hoc network (Aggarwal & Liu, 2005), although the theory behind the PSAPPSAP automaton was not as formally developed in that paper as it is in this current paper. A key feature of LA that makes them applicable to a broad range of applications is their ability to combine rapid and accurate convergence with a low computational complexity and better interpretability.

A variety of frameworks have been set up for the design of such LA. When the action probabilities of each state remain time-invariant, they are referred to as a fixed-structure stochastic automaton (FSSA). When the action probabilities change in time, they are referred to as a variable-structure stochastic automaton (VSSA). Tsetlin (1962) started the work on LA by considering the problem of finding an optimal action out of a set of allowable actions and attempted to address this problem using fixed-structure stochastic automata. A detailed review presented by Varshavskii and Vorontsova (1964) indicated that interest later shifted to the study of VSSA, which appeared to be more adaptable. On the other hand, FSSAs are easier to implement and require less computation per time step. This was the motivation before this current study, just as it was for Economides and Kehagias (2002), to return to the FSSA idea and search for FSSA designs that perform as well or even better than corresponding VSSAs.

In this paper, the authors introduce the probabilistically switch-action-on-penalty automaton (PSAPPSAPA), an FSSA, and compare its behavior to that of several "classical" FSSAs. For conciseness, the PSAPPSAPA is also referred to by the symbol Ж. Key learning properties of the PSAPPSAPA that cannot be achieved using classical LA will also be identified. Figure 1 shows the fan-shaped structure of the transition diagram. Each branch of the fan consists of several states that make up a chain of length *D* and are "committed" to one of the actions available to the automaton. The length *D* of the branches is one parameter of the automaton called depth, while the number of branches is equal to the number of possible actions, *r*, is the other parameter of the automaton; in general, then, this will be Ж$_{(r,D)}$. The PSAPPSAPA can switch from its active state in any chain to the initial state of the next chain in the circle, on each penalty, with some finite probability. Because this action-switching probability in case of penalty can be selected in multiple ways, the PSAPPSAPA becomes a framework for developing different FSSAs.

The primary motivation for studying the PSAPPSAPA was the non-zero action-switching probability for all states, reflected in its fan-shaped structure. In general, the action-switching probability is zero for most states of FSSA, with deterministic action selection in each state simulated in previous studies. Automata designed under the VSSA framework continuously maintain an action-selection probability vector and, therefore, can select any of the available actions at any given instant. In essence, there always exists a finite probability for a VSSA-based LA to switch from any action to any of the available actions in the future. This characteristic of VSSAs makes them more adaptable. By incorporating the action-switching-on-penalty feature in an FSSA, the aim of this current study was to design an FSSA that is more adaptable than previously proposed FSSAs, with its adaptability comparable to classical VSSAs. The presence of non-zero action-switching probability in every state in PSAPPSAPA increases the probability flow from one branch to the next in the LA and thus makes it more adaptable than classical FSSAs.

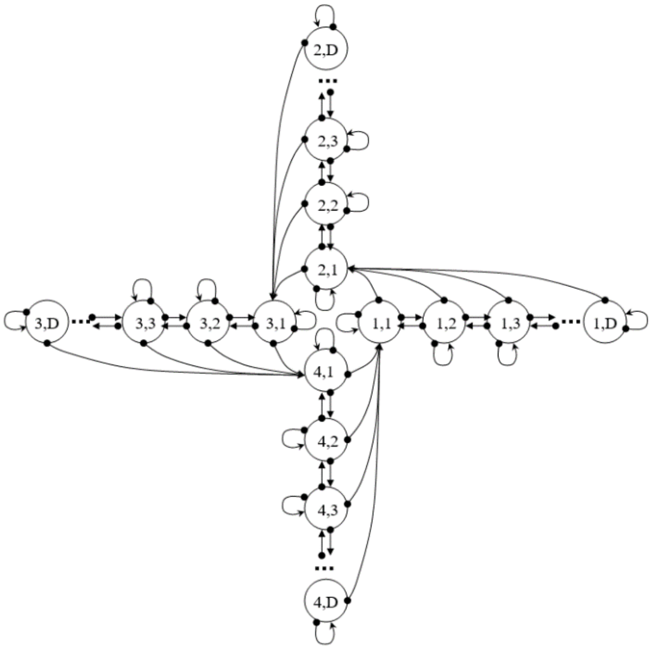


Figure 1. The PSAP$^{(r,D)}$ automaton with $r = 4$.

An essential feature of the PSAPPSAPA is that the authors designed the state transitions in response to penalty to always be probabilistic. Analytical and simulation results by previous researchers (Economides & Kehagias, 2002) indicate that the performance of LA possessing deterministic state transitions in response to reward, and probabilistic state transitions in response to penalty can asymptotically approach optimality in any environment. Therefore, the different action-switching configurations within this reward-deterministic/penalty-probabilistic state-transition framework were chosen for this current study.

Another motivation for studying LA is the apparently stochastic, randomized behavior of biological learning systems (Tsetlin, 1962). It has been shown that stochastic LA can perform better than their deterministic counterparts (Economides & Kehagias, 2002; Oommen & Christensen, 1988). However, a direct answer to the necessity of random behavior in learning systems has defied researchers for decades, primarily because of the existence of deterministic counterparts of stochastic LA simulated in previous studies (Narendra & Thathachar, 2012). The PSAPPSAPA proposed in this paper does not have a non-trivial deterministic counterpart. For example, if the action-switching is made deterministic in the 2-action PSAPPSAPA, the automaton degrades into a trivial two-state deterministic Tsetlin automaton, irrespective of the depth of the PSAPPSAPA. It is this characteristic of the PSAPPSAPA that served as the motivation in this current study to compare its behavior with classical FSSA that, unlike the PSAPPSAPA, have both deterministic and stochastic non-trivial versions (Narendra & Thathachar, 2012).

Fundamental Concepts of Stochastic LA

The standard mathematical description of the LA model involves the definition of the automaton itself, the environment with which it interacts, the objective of the interaction, and the learning method. For purposes of the current description, time is represented as a series of discrete instants separated by regular intervals, with one such instant being recognized as the first instant. A more detailed description is available in the study by (Economides & Kehagias, 2002). Environment is defined by a triple $\{A, B, C\}$, where:

$A \equiv \{\alpha_i\}$, $i = 1, 2, \ldots, r$ is the set of actions (input to the environment), where the action at any instant n is represented as $\alpha(n)$

$B \equiv \{\beta_j\}$ $j = 0, 1$ is the set of responses (output of environment), where 0 indicates a reward and 1 indicates a penalty; the actual response at any instant n is represented as $\beta(n)$

$C \equiv \{c_i\}$ i, $i = 1, 2, \ldots, r$ is a penalty probability set, which is unknown to the automaton, with c_i corresponding to action i, such that $\Pr[\beta(n) = 1 \mid \alpha(n) = \alpha_i] = c_i$

Note that the above definition holds for a stationary environment in which the penalty probability corresponding to each action is independent of time. For a non-stationary environment, however, the penalty probabilities change with time and a more accurate representation of the relationship between action and penalty is
$\Pr[\beta(n) = 1 \mid \alpha(n) = \alpha_i] = c_i(n)$.

Automaton is defined by a quintuple $\{\Phi, A, B, G(), F(|,,)\}$, where,

$\Phi \equiv \{\varphi_k\}$, $k = 1, 2, \ldots, s$ is the set of the internal states

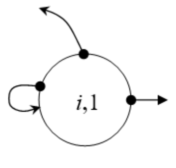
$A \equiv \{\alpha_i\}$, $i = 1, 2, \ldots, r$ is the set of actions (output of the automaton)

$B \equiv \{\beta_j\}$ $j = 0, 1$ is the set of responses (input to the automaton)

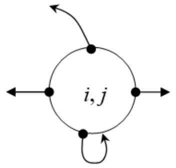
$G():\Phi \rightarrow A$ is the action selection function for choosing the action corresponding to the present state

Each state is associated with one specific action such that the automaton takes the same action each time it is in a given state
$F(l \mid k,i,j) = \Pr[\Phi(n+1) = \varphi_l \mid \Phi(n) = \varphi_k, \alpha(n) = \alpha_i, \beta(n) = \beta_j]$
is the conditional state-transition probability function for choosing the next state, depending on the present state, the action selected, and the environment response. Note that

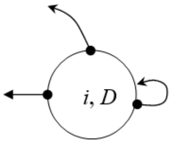
$$\sum_l F\left(l \middle| k,i,j\right) = 1, \forall k,i,j$$



(a) Initial state.



(b) Intermediate state.



(c) Terminal state.

Figure 2. Key state transitions in the PSAPA.

The above description of the class of automata considered in this study can be contrasted with the usual characterization of VSSAs in terms of the time-varying action-selection probability vector $p(n) \equiv [p_1(n)\ p_2(n)\ \ldots\ p_r(n)]$ and the associated learning algorithm Γ: $(n+1) \equiv \Gamma\ (p(n), \alpha(n), \beta(n))$ that updates the action-probability vector at any instant $n+1$, based on the action-selection probability at instant n, $p(n)$, actual action selected, $\alpha(n)$, and the environment response β (n). Note that the automata presented here belong to the FSSA rather than the VSSA class. For a stationary environment, it is desirable to have the automaton select the action, α^*, associated with the minimum penalty probability:

$$c^* \equiv \min_i \{c_i\}$$

Automaton performance is usually evaluated by the average cost for a given $p(n)$:

$$p(n): M(n) \equiv E\left[\beta(n) \middle| p(n)\right] = \sum_{i=1}^{r} c_i p_i(n)$$

a pure-chance automaton selects actions with equal probabilities for which the average cost is the mean of the penalty probabilities:

$$M_0(n) = (1/r)\sum_{i=1}^{r} c_i$$

An LA learns about the environment over multiple action-selection and reward/penalty instances, and attempts to reduce $M(n)$. An LA that asymptotically behaves better than a pure-chance automaton and will, in the limit, have an average cost of $\lim_{n\to\infty} E[M(n)] < M_0$ is termed as expedient. Similarly, an LA is said to be optimal if $\lim_{n\to\infty} E[M(n)] = c^*$. Previous studies (Narendra & Thathachar, 2012; Economides & Kehagias, 2002) have established that different LA can be optimal, provided the action penalty probabilities are constrained ($c^*<0.5$, for example). If an LA is optimal irrespective of the penalty probabilities of the actions, it is referred to as universally optimal.

For non-stationary environments, where limiting probabilities do not exist in general, the desirable qualities of an LA are still open to debate. In non-stationary environments, where the penalty probabilities change in time in an ergodic process, limiting probabilities still exist and the automaton must not only learn the characteristics of the environment but also "forget" old characteristics in favor of new ones in response to the time-varying situation. An optimal automaton may be too rigid to accommodate such requirements, because it may get locked in an action that is originally optimal but later becomes pessimal (Narendra & Thathachar, 2012). In such cases, ε-optimal automata that satisfy $\lim_{n\to\infty}E[M(n)] < c^* + \varepsilon$, with $\varepsilon > 0$ are more capable at responding to a changing environment. Please note that c^* could be equal to c_i, where i corresponds to different actions in time for a non-stationary environment of ergodic Markov process, as the penalty probabilities fluctuate with time, and the LA is supposed to recognize the action corresponding to this least-penalty probability in such a non-stationary environment. Thus, while optimality is desirable in stationary environments, a suboptimal performance may be preferable in nonstationary environments, where the optimal action varies with time.

The PSAPPSAP Learning Automaton

In this section, an r-action PSAPPSAPA with depth D will be denoted by $\text{Ж}_{(r,D)}$. As mentioned earlier, the action set is $A \equiv \{\alpha_1, \alpha_2, ..., \alpha_r\}$, the environment response set is $B \equiv \{0,1\}$ (reward and penalty), and the PSAPPSAPA has a fan-shaped structure consisting of r branches, each of which is made up of D states arranged as a chain. The first states of all chains form a circle of initial states. When the automaton is in one of the states of the i^{th} branch, it performs action α_i with probability one. In other words, each state is "committed" to a corresponding action. A state that is committed to action α_i and whose position along its branch's state-chain is d-1 states from the initial state, is denoted as $k = (i,d)$ and is said to have a depth of d. Figure 1 illustrates the fan-shaped structure along with the state-transition and action-selection mechanisms. Figures 2(a-c) show how the structure of the PSAPA consists of three different types of states—intermediate, terminal, and initial—respectively. Figure 2 shows the different types of state transitions possible from each state for a PSAPA. The action selection mechanism specifies the function G as $G(i,d) = \alpha_i$. For the purpose of conducting mathematical operations using probability matrices, the function G can also be represented as a probability matrix, G, as given by Equation 1:

$$\begin{aligned} &G\left(i^{'}\middle|(i,d)\right) \equiv \Pr\left[\alpha(n) = i^{'}\middle|\Phi(n) = (i,d)\right] = \delta_{ii^{'}}, \\ &\forall i, i^{'} = 1,2,...,r; \quad d = 1,2,...,D \end{aligned} \tag{1}$$

In other words, all probabilities above where $i' \neq i$ are equal to zero. To evaluate the expediency and optimality of the automaton, one must know the action probabilities $p_i(n)$, written in vector form as $p(n) = [p_1(n)\ p_2(n) .... p_r(n)]$. The probability of being at state $k = (i,d)$, at instant n: $\pi_k(n)$, is defined by writing it in vector form as $\pi(n) = [\pi_{(1,1)}(n)\ \pi_{(1,2)}(n)\ ...\ \pi_{(1,D)}(n)\ ...\pi_{(r,1)}(n)\ \pi_{(r,2)}(n)\ ...\ \pi_{(r,D)}(n)]$, thus yielding the relationship between action probabilities and state probabilities given by Equation 2:

$$\begin{aligned} p_i(n) &= \sum_{d} \sum_{i^{'}} \pi_{(i^{'},d)}(n) \\ G\left(i\middle|(i^{'},d)\right) &= \sum_{d} \pi_{(i,d)}(n) \end{aligned} \tag{2}$$

Hence, both the learning behavior and optimality properties depend on the state probabilities, $\pi(n)$, which in turn depend on the state transition mechanism defined by the probabilities, as given by Equation 3:

$$F\left(k^{'}\middle|k,i,j\right) = \Pr\left[\Phi(n+1) = k^{'}\middle|\Phi(n) = k,\ \ \alpha(n) = \alpha_i, \beta(n) = \beta_j\right] \tag{3}$$

where,

$$k^{'} = \left(i^{'}, d^{'}\right)$$

These probabilities depend on the current state, action, and response. Several possible choices of F are presented here. For all of these choices, the state process $\Phi(n)$ is an ergodic Markov chain with state transition matrix P, where $P_{k',k} = \Pr[\Phi(n+1) = (i',d')|\ \Phi(n) = (i,d)]$ in the presence of an environment penalty probability set $\{c_i\}$. Hence, $\lim_{n\to\infty} \pi(n) = \pi$. Here, π is the unique limiting (equilibrium) probability vector $\pi = \pi_{i,d}$, where i=0,1,2, … r, d=1,2,...D. Subsequently, when proposing the different FSSA, the limiting behavior of the automata will be investigated by deriving formulae for the limiting probability of the ith action as n→∞, which is $\lim_{n\to\infty} p_i(n) = p_i$ for a given penalty probability set $\{c_i\}$. Figure 1 shows the generic PSAP structure (for r=4). Figure 2 shows the complete set of state transitions available in response to reward and penalty. The conditional probability of changing the action in the case of penalty (i.e., β=1, while in the dth state by θ_d) is given by Equation 4:

$$\begin{aligned} &F\left((i^{'},1)\middle|(i,d),i,1\right) = \theta_d \\ &\forall\ \ i = 0,1,...,r-1 \\ &i^{'} = (i+1)(\operatorname{mod} r) \\ &d = 1,2,...D \end{aligned} \tag{4}$$

In the state of equilibrium, the total probability to change the branch from i to $(i+1)(\text{mod } r)$ at each step of the process is given by Equation 5:

$$\xi_i = \sum_{d=1}^{D} c_i \theta_d \pi_{i,d} \tag{5}$$

An important property of the equilibrium state of PSAPA is given by the proposition of Equation 6:

$$\xi_i = \xi \text{ for all } i = 1,2,...,r-1 \tag{6}$$

Offered as a proof: ξ_i is equal to the total probability flow from branch i to branch $(i+1)(\text{mod } r)$ in the limiting case as $n \to \infty$. At the equilibrium, the incoming flow of probabilities to every branch must be equal to the probability flow leaving the branch, which therefore yields Equation 7:

$$\xi_0 = \xi_1, \xi_1 = \xi_2, \xi_1 = \xi_2, ..., \xi_{r-1} = \xi_0 \tag{7}$$

Thus, all ξ_i are equal: $\xi_i = \xi_0 = \xi$; $i = 0,1,\ldots,r\text{-}1$

With respect to F, Figure 1 shows three different schemes of the generic PSAPA structure, each restricting the state transitions available in different ways. The response to reward is deterministic and identical in all three schemes, with the response to penalty being probabilistic and different from each other in all three schemes.

Ambivalent Ж$_{(r,D)}$

Figures 3(a-c) show that, for this scheme, reward and penalty cause state transitions according to the following rules.

1. When in an initial state $(i,1)$, if rewarded (Figure 3c, $\beta = 0$) go to state $(i,2)$ with probability one, according to Equation 8:

$$\begin{gathered} F\big((i,2)\big|(i,1),i,0\big) = 1 \\ \forall \;\; i = \{0,1,2,...,r-1\} \end{gathered} \tag{8}$$

If punished (Figure 3c, $\beta = 1$), transit to the initial state of the next branch [i.e., $((i+1)(\text{mod } r),1)$] in the r-action PSAPA, with probability θ_1, and stay in state $(i,1)$ with probability $1\text{-}\theta_1$, according to Equation 9:

$$\begin{gathered} F\big((i',1)\big|(i,1),i,1\big) = \theta_1, \quad F\big((i,1)\big|(i,1),i,1\big) = 1-\theta_1 \\ \forall \;\; i = \{0,1,2,...,r-1\}, \quad i' = (i+1)(\text{mod}\, r) \end{gathered} \tag{9}$$

2. When in an intermediate state (i,d), if rewarded (Figure 3a, $\beta = 0$), go to state $(i,d+1)$ with probability one, according to Equation 10:

$$\begin{gathered} F\big((i,d+1)\big|(i,d),i,0\big) = 1 \\ \forall \;\; i = \{0,1,2,...,r-1\}, \quad 1 < d < D \end{gathered} \tag{10}$$

If punished (Figure 3a, $\beta = 1$), transit to the initial state of the next branch [i.e., $((i+1)(\text{mod } r),1)$], in the r-action PSAPA, with probability θ_d, and stay in state (i,d) with probability $1\text{-}\theta_d$, according to Equation 11:

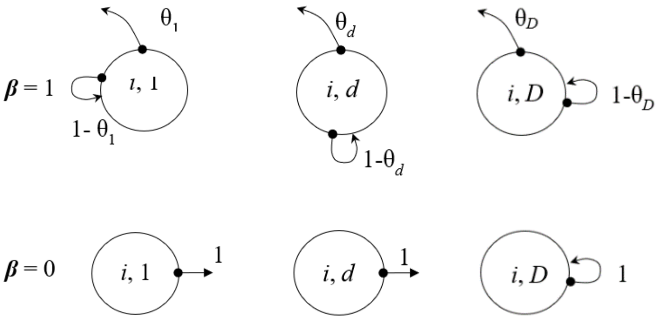
$$\begin{gathered} F\big((i',1)\big|(i,d),i,1\big) = \theta_d, \quad F\big((i,d)\big|(i,d),i,1\big) = 1-\theta_d \\ \forall \;\; i = \{0,1,2,...,r-1\}, \quad 1 < d < D, \quad i' = (i+1)(\text{mod}\, r) \end{gathered} \tag{11}$$

3. When in a terminal state (i,D)(Figure 3b, $\beta = 0$), if rewarded, stay in the same state with probability one, according to Equation 12:

$$\begin{gathered} F\big((i,D)\big|(i,D),i,0\big) = 1 \\ \forall \;\; i = \{0,1,2,...,r-1\} \end{gathered} \tag{12}$$

If punished (Figure 3b, $\beta = 1$), transit to the initial state of the next branch [i.e., $((i+1)(\text{mod } r),1)$], in the r-action PSAPA, with probability θ_D, and stay in state (i, D) with probability $1\text{-}\theta_D$, according to Equation 13:

$$\begin{gathered} F\big((i',1)\big|(i,D),i,1\big) = \theta_D, \quad F\big((i,D)\big|(i,D),i,1\big) = 1-\theta_D \\ \forall \;\; i = \{0,1,2,...,r-1\}, \quad i' = (i+1)(\text{mod}\, r) \end{gathered} \tag{13}$$



(a) Initial state. (b) Intermediate state. (c) Terminal state.

Figure 3. The canonical state-transition configuration (ambivalent PSAPA).

Equations 8, 10, and 12 persist for the other two models presented later and will not be repeated for the reward case for the two other automata. From $F(\bullet|\bullet,\bullet,\bullet)$ the limiting state probabilities and action probabilities can be computed and the expediency and optimality of the automaton evaluated. Here, however, only the results of the analysis from this current study are presented; detailed derivations are given by Aggarwal, Liu, and Levitin (2022). The nonzero elements of P turned out to be as predicted by Equation 14, while all other elements of P were zero.

$$P_{(i,d),(i,d+1)} = 1-c_i, P_{(i,d),(i,d)} = c_i\left(1-\theta_d\right), \quad P_{(i,D-1),(i,D)} = 1-c_i,$$
$$P_{(i,D),(i,D)} = \left(1-c_i\right)+c_i\left(1-\theta_D\right) = 1-c_i\theta_D, \quad P_{(i,d),(i',1)} = c_i\theta_D, \tag{14}$$
$$\forall \;\; i = \{0,1,2,...,r-1\}, \quad i' = (i+1)(\bmod r)$$

It is obvious from Equation 14 that, for all the diagonal elements of P, $P_{(i,d),(i,d)}>0$. Furthermore, it is easy to confirm that $P^{D+r\text{-}1}>0$. Intuitively, this corresponds to the fact that, in r steps, one can move from any state to the initial state of any branch, including the initial state of the current branch. Furthermore, in another D-1 steps, one can move from the initial state of a branch to any other state in the branch with positive probability. In other words, in D+r-1 steps, one can move from any state to any other state in the automaton with positive probability. Hence, the state process Φ(n), corresponding to the Ambivalent Ж$_{(r,D)}$ automaton, is irreducible, aperiodic and, as a consequence, ergodic (Narendra & Thathachar, 2012). Using Equation 14, Equation 15 can be obtained for the limiting state probabilities $\pi_{i,d}$.

$$\begin{aligned} &\xi_i = \xi = \sum_{d=1}^{D} c_i\theta_d\pi_{i,d}, \quad \pi_{i,1}\frac{\xi}{\left[\left(1-c_i\left(1-\theta_1\right)\right)\right]}, \\ &\pi_{i,d}\frac{\pi_{i,d-1}\left(1-c_i\right)}{\left[1-c_i\left(1-\theta_d\right)\right]}, \quad \pi_{i,D}\frac{\pi_{i,D-1}\left(1-c_i\right)}{c_i\theta_D} \end{aligned} \tag{15}$$

Equation 15 was derived using the assumption that the probability flow into any state at equilibrium will be equal to the probability flow out of the state, thereby yielding Equation 16:

$$\begin{aligned} &\pi_{i,d}\frac{\xi\left(1-c_i\right)^{d-1}}{\prod\limits_{k=1:d}\left[1-c_i\left(1-\theta_k\right)\right]} \\ &\pi_{i,D}\frac{\xi\left(1-c_i\right)^{D-1}}{c_i\theta_D\prod\limits_{k=1:D-1}\left[1-c_i\left(1-\theta_k\right)\right]} \end{aligned} \tag{16}$$

Here, ξ is the joint probability of three events: (1) the last active state was in the i^{th} branch of the automaton; (2) the action selected was punished; and, (3) the automaton switches its current state to the next branch. It is indicative of the relative frequency with which action-switching is occurring between any two actions corresponding to adjacent branches in the automaton, or the flow rate of the current state from one branch to the next branch. The derivation of the previous equations is based on the observation that, at equilibrium, the probability ξ is the same for all branches of the automaton (see the proposition of Equation 6). For an r-action automaton, the action probabilities for the u^{th} and v^{th} actions, p_u and p_v, respectively, are given by Equation 17. And, taking the ratio of the two statements in Equation 17 eliminates ξ , yielding Equation 18:

$$\begin{aligned} p_u &= \frac{\xi\left(1-c_u\right)^{D-1}}{c_u\theta_D\prod\limits_{k=1:D-1}\left[1-c_u\left(1-\theta_k\right)\right]}+\sum_{d=1}^{D-1}\frac{\xi\left(1-c_u\right)^{d-1}}{\prod\limits_{k=1:d}\left[1-c_u\left(1-\theta_k\right)\right]} \\ p_v &= \frac{\xi\left(1-c_v\right)^{D-1}}{c_v\theta_D\prod\limits_{k=1:D-1}\left[1-c_v\left(1-\theta_k\right)\right]}+\sum_{d=1}^{D-1}\frac{\xi\left(1-c_v\right)^{d-1}}{\prod\limits_{k=1:d}\left[1-c_v\left(1-\theta_k\right)\right]} \end{aligned} \tag{17}$$

$$\Omega_D = \frac{p_u}{p_v} = \frac{\dfrac{\left(1-c_u\right)^{D-1}}{c_u\theta_D\prod\limits_{k=1:D-1}\left[1-c_u\left(1-\theta_k\right)\right]}+\sum\limits_{d=1}^{D-1}\dfrac{\left(1-c_u\right)^{d-1}}{\prod\limits_{k=1:d}\left[1-c_u\left(1-\theta_k\right)\right]}}{\dfrac{\left(1-c_v\right)^{D-1}}{c_v\theta_D\prod\limits_{k=1:D-1}\left[1-c_v\left(1-\theta_k\right)\right]}+\sum\limits_{d=1}^{D-1}\dfrac{\left(1-c_v\right)^{d-1}}{\prod\limits_{k=1:d}\left[1-c_v\left(1-\theta_k\right)\right]}} \tag{18}$$

Based on the motivation for the machine learning algorithm derived from the extended discrete Kalman filter algorithm by Aggarwal and Kumar (1997), the parameters in the previous equations, θ_d, were chosen as given in Equation 19:

$$\theta_d = \frac{1}{d}, \quad \theta_D = \frac{1}{D} \tag{19}$$

Using Equation 19, the ratio of probabilities in Equation 18 can be rewritten as shown in Equation 20:

$$\begin{aligned} &\Omega_D \approx \frac{1-2c_v}{1-2c_u}\left[\frac{\left(1+\dfrac{b_v}{D}\right)^{(b_v+0.5)}}{\left(1+\dfrac{b_u}{D}\right)^{(b_u+0.5)}}\right]\frac{\Gamma\left(b_u\right)}{\Gamma\left(b_v\right)}D^{(b_v-b_u)} \\ &\forall \quad b_u < b_v < 1 \end{aligned} \tag{20}$$

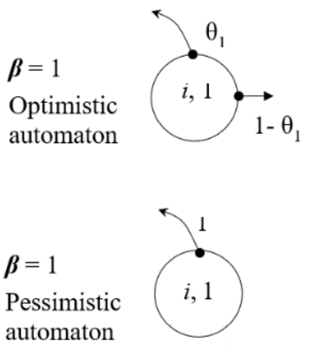
where, $b = c/(1\text{-}c)$, (Appendix A, (A1.9) (Aggarwal et al., 2022).

Thus, when $b_u < b_v < 1$, $\Omega_D \rightarrow \infty$ as $D \rightarrow \infty$ and the automaton is ε-optimal when all the penalty probabilities are <0.5. Also, if $b_u < 1$ and $b_v > 1$, this yields Equation 21, as shown in Appendix A, (A1.10) (Aggarwal et al., 2022).

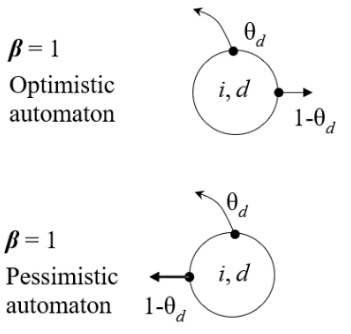
$$\begin{aligned} &\Omega_D \approx \frac{2c_v-1}{1-2c_u}\frac{\Gamma\left(b_u\right)}{\left(1+\dfrac{b_u}{D}\right)^{(b_u+0.5)}}D^{(1-b_u)} \\ &\forall \quad b_u < 1 \;\text{ and }\; b_v > 1 \end{aligned} \tag{21}$$

Furthermore, Ω_D is proportional to $D^{(1\text{-}bu)}$ and $\Omega_D \rightarrow \infty$ as $D \rightarrow \infty$ and the automaton is ε-optimal when at least one of the penalty probabilities is <0.5. However, if b_1 and b_2 are both greater than one, then $\Omega_D \rightarrow (2c_v\text{-}1)/(2c_u\text{-}1)$ as $D \rightarrow \infty$ (Appendix A, (A1.11) (Aggarwal et al., 2022) and the automaton is not ε-optimal in such an environment, when all the penalty probabilities are >0.5. Additionally, for the

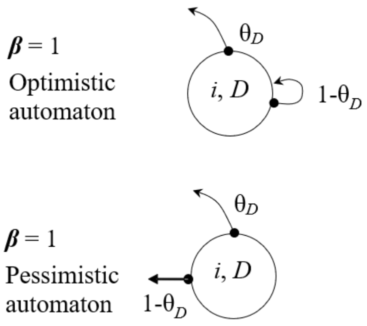
Ambivalent Ж to be ε-optimal, at least one of the penalty probabilities should be less than 0.5. As suggested previously by other researchers (Economides & Kehagias, 2002; Oommen & Christensen, 1988), this condition can be enforced by treating 50% of randomly selected penalties as rewards, thereby reducing all effective penalty probabilities by 50%. However, using this approach, the Ambivalent Ж requires a larger set of input data to get trained, and this adversely affects its convergence rate and adaptability in non-stationary environments (Liu, 2006). The Optimistic PSAPA is universally ε-optimal and does not suffer from this deficit.



(a) Initial state.



(b) Intermediate state.



(c) Terminal state.

Figure 4. Two alternative configurations of the PSAP automaton [i.e., the Optimistic (Top) and Pessimistic (Bottom) PSAF automata].

Optimistic Ж$_{(r,D)}$

In this scheme, state transitions in response to reward are identical to the Ambivalent Ж (Equations 8, 10, and 12). However, Figure 4 shows that, for the intermediate, terminal, and initial states, the state transitions in response to penalty differ from the Ambivalent Ж. That is:

1. When in an initial state (i,1), if punished (Figure 4c, β = 1, Optimistic automaton), transit to the initial state of the next branch of the r branches [i.e., ((i +1) (mod r),1)] in the r-action PSAPA, with probability θ_1, and transit to state (i,2) with probability 1-θ_1. Refer to Equation 22:

$$F\left(\left(i^{'},1\right)\middle|\left(i,1\right),i,1\right)=\theta_1,\quad F\left(\left(i,2\right)\middle|\left(i,1\right),i,1\right)=1-\theta_1 \qquad (22)$$
$$\forall \quad i=\left\{0,1,2,\ldots,r-1\right\},\quad i^{'}=\left(i+1\right)\left(\operatorname{mod} r\right)$$

2. When in an intermediate state (i,d), if punished (Figure 4a, β = 1, Optimistic automaton), transit to the initial state of the next branch of the r branches [i.e., ((i +1)(mod r),1)] in the r-action PSAPA, with probability θ_d, and transit to state (i,d+1) with probability 1-θ_d. Refer to Equation 2:

$$F\left(\left(i^{'},1\right)\middle|\left(i,d\right),i,1\right)=\theta_d,\quad F\left(\left(i,d+1\right)\middle|\left(i,d\right),i,1\right)=1-\theta_d \qquad (23)$$
$$\forall \quad i=\left\{0,1,2,\ldots,r-1\right\},\quad 1<d<D,\quad i^{'}=\left(i+1\right)\left(\operatorname{mod} r\right)$$

3. When in a terminal state (i,D), if punished (Figure 4b, β = 1, Optimistic automaton), transit to the initial state of the next branch of the r branches [i.e., ((i +1) (mod r),1)] in the r-action PSAPA, with probability θ_D, and stay in state (i,D) with probability 1-θ_D. Refer to Equation 24:

$$F\left(\left(i^{'},1\right)\middle|\left(i,D\right),i,1\right)=\theta_D,\quad F\left(\left(i,D\right)\middle|\left(i,D\right),i,1\right)=1-\theta_D \qquad (24)$$
$$\forall \quad i=\left\{0,1,2,\ldots,r-1\right\},\quad i^{'}=\left(i+1\right)\left(\operatorname{mod} r\right)$$

Using Equations 8, 10, 12, 22-24, the limiting state probabilities and action probabilities can be computed and the expediency and optimality of the automaton can be evaluated. Here, however, only the results of the analysis from this current study are presented; detailed derivations are given in Appendix B (Aggarwal et al., 2022). The nonzero elements of P turned out to be as predicted by Equation 25, while all other elements of P were zero.

$$\begin{aligned}
&P_{(i,d),(i,d+1)}=\left(1-c_i\right)+c_i\left(1-\theta_d\right)=1-c_i\theta_d,\\
&P_{(i,D),(i,D)}=\left(1-c_i\right)+c_i\left(1-\theta_D\right)=1-c_i\theta_D,\\
&P_{(i,d),(i^{'},1)}=c_i\theta_D,\\
&\forall \quad i=\left\{0,1,2,\ldots,r-1\right\},\quad i^{'}=\left(i+1\right)\left(\operatorname{mod} r\right)
\end{aligned} \qquad (25)$$

It is obvious from Equation 25 that, for all the diagonal elements of P, $P_{(i,d),(i,d)}>0$. Furthermore, it is easy to confirm that $P^{D+r-1}>0$. Therefore, using the same logic as in the previous section, it can be inferred that the state process $\Phi(n)$, corresponding to the Optimistic Ж$_{(r,D)}$ automaton is irreducible, aperiodic and, as a consequence, ergodic (Narendra & Thathachar, 2012). From P in Equation 25, the limiting state probabilities, $\pi_{i,d}$, can be computer, which turn out to be given by Equations 26 and 27:

$$\begin{aligned}&\xi=\sum_{d=1}^{D} c_i\theta_d\pi_{i,d},\quad \pi_{i,1}=\xi,\\ &\pi_{i,d}=\pi_{i,d-1}\left(1-c_i\theta_{d-1}\right),\quad \pi_{i,D}\,\frac{\pi_{i,D-1}\left(1-c_i\theta_{D-1}\right)}{c_i\theta_D}\end{aligned}\tag{26}$$

$$\pi_{i,d}=\xi\prod_{k=1:d-1}\left(1-c_i\theta_k\right),\quad \pi_{i,D}\,\frac{\xi\prod\limits_{k=1:D-1}\left(1-c_i\theta_k\right)}{c_i\theta_D}\tag{27}$$

For an r-action automaton, the action probabilities for any two actions, actions u and v without loss of generality, for example (i.e., p_u and p_v, respectively), are given by Equation 28:

$$\begin{aligned}p_u&=\frac{\xi\prod\limits_{d=1:D-1}\left(1-c_u\theta_d\right)}{c_u\theta_D}+\sum_{d=2}^{D-1}\xi\prod_{k=1:d-1}\left(1-c_u\theta_k\right)\\ p_v&=\frac{\xi\prod\limits_{d=1:D-1}\left(1-c_v\theta_d\right)}{c_v\theta_D}+\sum_{d=2}^{D-1}\xi\prod_{k=1:d-1}\left(1-c_v\theta_k\right)\end{aligned}\tag{28}$$

And, taking the ratio of the two statements in Equation 28 eliminates ξ , yielding Equation 29:

$$\Omega_D=\frac{p_u}{p_v}=\frac{\dfrac{\prod\limits_{d=1:D-1}\left(1-c_u\theta_d\right)}{c_u\theta_D}+1+\sum\limits_{d=2}^{D-1}\prod\limits_{k=1:d-1}\left(1-c_u\theta_k\right)}{\dfrac{\prod\limits_{d=1:D-1}\left(1-c_v\theta_d\right)}{c_v\theta_D}+1+\sum\limits_{d=2}^{D-1}\prod\limits_{k=1:d-1}\left(1-c_v\theta_k\right)}\tag{29}$$

where, θ_k is selected, as was the case in Equation 19, and yields Equation 30. [See Appendix B, (A2.6) (Aggarwal et al., 2022).]

$$\begin{aligned}&\Omega_D\approx\frac{\Gamma\left(c_v+1\right)\Gamma\left(2-c_v\right)}{\Gamma\left(c_u+1\right)\Gamma\left(2-c_u\right)}\frac{\left\{\left(1-c_u\right)D\Gamma\left(c_u\right)D^{--c}u+c_u\left(D-c_u-1\right)\Gamma\left(c_u\right)D^{--c}u\right\}}{\left\{\left(1-c_v\right)D\Gamma\left(c_v\right)D^{--c}v+c_v\left(D-c_v-1\right)\Gamma\left(c_v\right)D^{--c}v\right\}}\\ &\forall\quad D>>1\end{aligned}\tag{30}$$

Thus, the following analysis is similar to that for the Ambivalent Ж and the ratio of probabilities will be proportional to $D^{(cv\text{-}cu)}$ for large values of D. Therefore, the Optimistic Ж is ε-optimal for all penalty probabilities, since $\Omega_D \rightarrow \infty$ as $D \rightarrow \infty$ when $c_v > c_u$.

Pessimistic Ж$_{(\mathrm{r,D})}$

In this scheme, state transitions in response to reward are identical to the Ambivalent Ж (Equations 8, 10, and 12). However, Figure 4 shows that state transitions for the intermediate, terminal, and initial states in response to penalty differ from the Ambivalent Ж.

1. When in an initial state $(i,1)$, if punished (Figure 4c, $\beta = 1$, Pessimistic automaton), transit to the initial state of the next branch of the r branches [i.e., $((i+1)(\mathrm{mod}\ r),1)$] in the r-action PSAPA, with probability 1. Refer to Equation 31:

$$\begin{aligned}&F\left(\left(i',1\right)\middle|\left(i,1\right),i,1\right)=1\\ &\forall\quad i=\left\{0,1,2,\ldots,r-1\right\},\quad i'=\left(i+1\right)\left(\mathrm{mod}\,r\right)\end{aligned}\tag{31}$$

2. When in an intermediate state (i,d), if punished (Figure 4a, $\beta = 1$, Pessimistic automaton), transit to the initial state of the next branch of the r branches [i.e., $((i+1)(\mathrm{mod}\ r),1)$] in the r-action PSAPA, with probability θ_d, and transit to state $(i,d\text{-}1)$ with probability $1\text{-}\theta_d$. Refer to Equation 32:

$$\begin{aligned}&F\left(\left(i',1\right)\middle|\left(i,d\right),i,1\right)=\theta_d,\quad F\left(\left(i,d-1\right)\middle|\left(i,d\right),i,1\right)=1-\theta_d\\ &\forall\quad i=\left\{0,1,2,\ldots,r-1\right\},\quad 1<d<D,\quad i'=\left(i+1\right)\left(\mathrm{mod}\,r\right)\end{aligned}\tag{32}$$

3. When in a terminal state (i,D), if punished (Figure 4b, $\beta = 1$, Pessimistic automaton), transit to the initial state of the next branch of the r branches [i.e., $((i+1)(\mathrm{mod}\ r),1)$] in the r-action PSAPA, with probability θ_D, and transit to $(i,D\text{-}1)$ with probability $1\text{-}\theta_D$. Refer to Equation 33:

$$\begin{aligned}&F\left(\left(i',1\right)\middle|\left(i,D\right),i,1\right)=\theta_D,\quad F\left(\left(i,D-1\right)\middle|\left(i,D\right),i,1\right)=1-\theta_D\\ &\forall\quad i=\left\{0,1,2,\ldots,r-1\right\},\quad i'=\left(i+1\right)\left(\mathrm{mod}\,r\right)\end{aligned}\tag{33}$$

Using Equations 8, 10, 12, and 31-33, the limiting state probabilities and action probabilities can be computed and the expediency and optimality of the automaton can be proved. Here, however, only the results of the analysis from this current study are presented; detailed derivations are given by Aggarwal et al. (2022), since the derivations are rather long for the Pessimistic PSAPA model. The nonzero elements of P turned out to be as predicted by Equation 34, while all other elements of P were zero.

$$\begin{aligned}&P_{(i,d),(i,d+1)}=1-c_i,\quad P_{(i,d),(i,d-1)}=c_i\left(1-\theta_d\right),\\ &P_{(i,d),\left(i',1\right)}=c_i\theta_d,\quad P_{(i,D),(i,D)}=1-c_i,\quad P_{(i,1),\left(i',1\right)}=c_i\\ &\forall\quad 1<d<D\ \text{and}\ i=\left\{0,1,2,\ldots,r-1\right\},\quad i'=\left(i+1\right)\left(\mathrm{mod}\,r\right)\end{aligned}\tag{34}$$

From Equation 34, it is obvious that, for a given state (i,d), the diagonal element in P^2 corresponding to that state (i.e., $P^2_{(i,d),(i,d)}$) is larger than zero. Intuitively, this also follows from the observation that, although like the two other automata in that every state in the Pessimistic Ж has its probability outflow equal to its state probability after every time step, it also has positive probability inflow after two time steps. This is because, unlike the other two automata, the probability outflow following punishment is also inward within a branch, rather than just outward in the case of the other two automata. Furthermore, it is easy to confirm that all the elements of P^{D+r-1} are larger than zero. Hence, the state process $\Phi(n)$, corresponding to the Pessimistic Ж$_{(r,D)}$ automaton, is irreducible, aperiodic and, as a consequence, ergodic (Narendra & Thathachar, 2012). From P in Equation 34, the limiting state probabilities can be computed, which turn out to be solutions of Equation 35:

$$\xi = \sum_{d=1}^{D} c_i \theta_d \pi_{i,d}, \quad \pi_{i,1} = \left(1-\theta_2\right) c_i \pi_{i,2} + \xi,$$
$$\pi_{i,d} = \pi_{i,d+1}\left(1-\theta_{d+1}\right)c_i + \pi_{i,d-1}\left(1-c_i\right), \quad \pi_{i,D} = \pi_{i,D-1}\frac{\left(1-c_i\right)}{c_i} \tag{35}$$

For an r-action automaton, the action probabilities for any two actions, actions u and v without loss of generality, for example (i.e., p_u and p_v, respectively), are given by the following statements:

$$p_u = \sum_{d=1}^{D} \pi_{u,d}, \quad p_v = \sum_{d=1}^{D} \pi_{v,d}$$

The ratio of the probabilities of the two actions, u and v, becomes then Equation 36:

$$\Omega_D = \frac{p_u}{p_v} = \frac{\xi \sum_{d=1}^{D} \bar{\pi}_{u,d}}{\xi \sum_{d=1}^{D} \bar{\pi}_{v,d}} = \frac{\sum_{d=1}^{D} \bar{\pi}_{u,d}}{\sum_{d=1}^{D} \bar{\pi}_{v,d}} \qquad \text{where, } \pi_{i,d} = \xi \bar{\pi}_{i,d}$$
$$\bar{\pi}_{i,D} = \frac{\left(1-c_i\right)^{D-1}}{K_D - \left(1-c_i\right) * K_{D-1}}; \quad \bar{\pi}_{i,D-1} = \frac{c_i}{\left(1-c_i\right)} \pi_{i,D}; \tag{36}$$
$$\bar{\pi}_{i,d} = a_d\left(c_i\right) + \gamma_d\left(c_i\right)\bar{\pi}_{i,d+1}; \quad K_d = K_{d-1} - c_i\left(1-c_i\right)\left(1-\frac{1}{d}\right) * K_{d-2}; \quad K_0 = K_1 = 1$$
$$a_d\left(c_i\right) = \frac{\left(1-c_i\right)^{(d-1)}}{K_d}; \quad \gamma_d\left(c_i\right) = \frac{1}{\left(1-c_i\right)}\left[1-\frac{K_{d+1}}{K_d}\right]$$

where, θ_d is selected, as in Equation 19.

Thus, as shown by Aggarwal et al. (2022), the ratio of the probabilities in Equation 36, Ω_D is proportional to $(D\text{-}1)^{(b'_v - b'_u)}$, where b' = c/(1-2c), if c_u and c_v are both less than 1/3. If $c_v > 1/3$ and $c_u < 1/3$, Ω_D is proportional to $(D\text{-}1)^{(1- b'_u)}$. If c_v, $c_u > 1/3$, Ω_D converges to a finite value as $D \rightarrow \infty$. Hence, the Pessimistic PSAPA is ε-optimal only if at least one of the penalty probabilities, c_i, is less than 1/3, since $\Omega_D \rightarrow \infty$ as $D \rightarrow \infty$ only for this case.

In summary, based on the results presented here, the Optimistic Ж is ε-optimal for all possible penalty probabilities. This result is significant, since an LA model that is universally ε-optimal without manipulating the penalty probabilities (Economides & Kehagias, 2002; Oommen & Christensen, 1988) has defied researchers for a long time. Furthermore, the PSAP automata are also easier to implement, thus requiring no floating-point multiplications, unlike VSSA frameworks. Finally, PSAP automata are mathematically more tractable, since they can be analyzed by the theory of finite Markov chains; the analysis of $L_{R\text{-}\varepsilon P}$ behavior requires the use of stochastic difference equations and an approximation argument (Narendra & Thathachar, 2012).

Conclusions and Future Work

In this paper, the authors presented a PSAPA framework for FSSA along with an analytical model of the asymptotic behavior of three of the many possible FSSA within that framework. It is worth noting that, of these three, only the Optimistic PSAPA is universally ε-optimal. This observation implies that universal ε-optimality results from very specific characteristics in any given FSSA. In general, previous researchers have claimed, implicitly or explicitly, that to achieve ε-optimality, 50% of penalties from the environment need to be randomly ignored and treated as rewards (Tsetlin, 1962). No such strategy has to be applied in the case of the Optimistic PSAPA. In contrast, the Pessimistic PSAPA would require that two-thirds of the penalties be ignored in order to become universally ε-optimal. This could mean that there exists an entire spectrum of FSSAs that would require ignoring different fractions of the penalties, besides 1/2 and 2/3.

The authors of this current study believe that the architecture of the different PSAPA should be able to shed some light on what strategies need to be present in an FSSA for it to be ε-optimal. For example, the states in the three automata presented in this paper have two broad classes of state transitions: inter-branch state transitions and intra-branch state transitions. While the inter-branch state transition probabilities are identical in all three automata, their intra-branch state transitions are distinctly different. So, the difference in their ε-optimality properties is a result of their intra-branch state transitions. However, the inter-branch state transitions also play an important role. Indeed, if θ becomes a constant (i.e., independent of the depth of a state d) then the behavior of PSAPA will be independent of D, and will just degenerate into the behavior of an $L_{N,N}$ automaton, where there is only one state per action (i.e., there are N states corresponding to N actions in total and all state transitions are deterministic). The authors are currently exploring different θ values as functions of depth, and plan present results from this analysis using simulations and analytics in future work. The FSSA framework presented in this paper has no non-trivial deterministic counterpart. FSSAs presented in previous studies have achieved ε-optimality by randomizing the response to a reward/penalty by a deterministic FSSA. In fact, this approach has also been used in the VSSA framework, where different techniques are used for estimating penalty probabilities, and then action selection is randomized based on these estimated values. It has been noted in previous research that action-selection schemes can be designed using multiple FSSAs, rather than a single FSSA, that will outperform the single FSSA. A corollary to this observation is that there exists a VSSA design corresponding to each FSSA design, based on estimating the probability of occupation of every state in the FSSA, and then using the state occupation probabilities to calculate action-selection probabilities (Oommen & Agache, 2001). However, the computational load in this case increases with an increase in the number of steps, thereby making these VSSA designs incapable of simulating optimality in real-world problems. Thus, the requirement for randomized action switching and finite computational load with an increasing number of possible actions and attempts/steps makes ε-optimal FSSA designs more likely for solving real-world problems.

The primary differentiating feature of PSAPA is highlighted by non-zero values of the state action-switching probability parameter θ. Non-zero values of this parameter ensure a non-zero action-switching probability in every state. If θ is set to zero, the 2-action Pessimistic PSAPA transforms into the Tsetlin automaton $L_{2N,2}$. Therefore, comparison of the dynamic behavior of the Pessimistic PSAPA and Tsetlin automaton, for example, can be used to clarify the impact of non-zero values of θ on PSAPA performance. Another FSSA with similar a response to penalty but a different response to reward is the Krinsky automaton. An FSSA with a similar response to reward but a different response to penalty is the Krylov automaton. An alternate strategy was proposed by Ponomarev (1964), where a horizontal row of action-switching states with alternate actions taken by adjacent states separate two vertical rows of non-action switching states that have the same response to reward and penalty as $L_{2N,2}$ in a 2-action selection environment. All these automata are described by Narendra and Thathachar (2012). A similar and more popular automaton was also proposed by Cover and Hellman (1970). The comparison of dynamic behavior of these automata with the Pessimistic PSAPA as well as other PSAPA will be pursued in future work.

Previous researchers have investigated ε-optimal automaton designs in the past, because designing a strictly optimal automaton would require an infinite number of states in the automaton. Ideally, the real goal of LA is to identify designs that can solve the action-selection problem optimally. An ε-optimal FSSA can approach such optimality, if we take into consideration the fact that, in the real world the number of steps is always finite, the computational load for an FSSA remains constant even as the number of steps increase, and the maximum depth of the active state at any instant increments at a lesser rate than the number of steps. For given values of r and D, the PSAPA achieves an order of reward probability different from that of the corresponding Tsetlin, or STAR automata, since the PSAPA achieve ε-optimality according to a power law versus depth rather than exponentially, unlike most LA.

There is a possibility that the larger number of states used by PSAPA to achieve the same level of reward probability results in better dynamic properties; this, too, will be explored in a follow-up publication by the current authors that will include detailed simulation results comparing the performance of PSAPA and other FSSAs in simple non-stationary environments. Note that the framework for LA dictates that the environment has only two responses, either a reward or a penalty, with no quantitative value. That was the framework used in this current study. In case a larger number of responses is considered, the reinforcement learning framework starts to resemble a supervised learning framework, since the response serves as a label that can be used to segment actions. The PSAPA has a non-zero action-switching probability in all its states, irrespective of the previous history. The time evolution of the automaton can also be described by a discrete-time finite-state Markov decision process. In future research, the authors aim to explore applications of the PSAPA that leverage these two properties, besides the ε-optimality characteristics.

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Biographies

PRATEEK S. AGGARWAL received his PhD in Biomedical Engineering from Boston University in 2003. He has been working as a data scientist at different companies since 2005, including Oracle Retail, Adobe, and JP Morgan & Chase. He is currently employed as a senior data scientist with MasterCard. Dr. Aggarwal is a member of IEEE and may be reached at prateekji@gmail.com

CHENHUI LIU works as a Principal Consultant in the Data Analytics group at Slalom Consulting, helping many corporate clients accelerate business outcomes with rapid insights backed by AI/ML. Her research interests include learning automaton design, efficient encoding and decoding of learning processes, AI and its applications to portfolio optimization and wealth management, default and bankruptcy prediction, and optimal design of learning paths with interactive cross-media systems. She received her PhD in Computer Engineering from Boston University in 2006. Dr. Liu is a member of IEEE and may be reached at Dr.chenhui.liu@gmail.com

LEV LEVITIN is a distinguished professor of engineering science in the Department of Electrical and Computer Engineering at Boston University. He has published over 200 papers, presentations, and patents. His research areas include information theory, quantum communication systems, physics of computation, quantum computing, quantum theory of measurements, mathematical linguistics, theory of complex systems, coding theory, theory of computer hardware testing, reliable computer networks, and bioinformatics. He is a life fellow of IEEE, a member of the International Academy of Informatics and other professional societies. Prof. Levitin may be reached at levitin@bu.edu

MATERIAL ANALYSIS OF THE MALLEABILITY AND APPLICATION OF A BIO-INSPIRED CUTTLEFISH FIN FOR AN AUTONOMOUS UNDERWATER VEHICLE

Kendra Kim, Arizona State University; Sangram Redkar, Arizona State University; Max Edward, University of Advancing Technology

Abstract

The mechanical properties of materials play a crucial role in experimental conditions. In the design utilization of a cuttlefish fin, the material required will need to be flexible. The choice of material can greatly impact the success of an application, as the material's mechanical properties determine its response to various stresses and strains. The application for underwater use with minimal disturbance of the environment is based on large deformations by rods and requires the ability to recover the original shape during repeated use. Additionally, the material's stiffness, strength, and elasticity all play a role in determining the flexibility and suitability for this application. In this study, the authors were not concerned with the overall force and movement of the vehicle, but instead focused on the importance of material properties for experimental conditions that require flexibility to achieve the desired results for this application. This included the confirmation of additive manufacturing gaps within this specific manufacturing application.

Introduction

In this paper, the authors discuss a specific application of an autonomous vehicle, as described by Kim (2023) in a bio-inspired cuttlefish fin design. In this design, the use of a fin was analyzed for biomimicry and considered in a software simulation. The review of material selection for additive versus non-additive solutions was considered within this evaluation. Including data sheets for testing structural design, areas of opportunity were identified that could be further discussed and analyzed. For example, silicon-poured material is more flexible than Formlabs Flexible 80A resin that is additively manufactured, because of the unique chemical properties of silicone. Silicone is a type of elastomer, which is a polymer with elastic properties that enables the design to stretch and deform without breaking or permanent deformation; this is because silicone has a low cross-linking density, meaning that the polymer chains are not tightly bound to each other.

The Formlabs Flexible 80A resin is a type of thermoplastic elastomer, which is a polymer with both thermoplastic and elastomeric properties. Thermoplastic elastomers typically have a higher cross-linking density compared to elastomers like silicone, which makes them less flexible (Formlabs, 2022). In a design of the fin, there is a base structure that utilizes a wave motion to propel an AUV. Figure 1 shows a simulation that was utilized for the control system and which showcases the movement of the fin in a wave motion. Figure 2 shows an additively manufactured version of this design intended to achieve a requirement for a cam system to be utilized in the design.

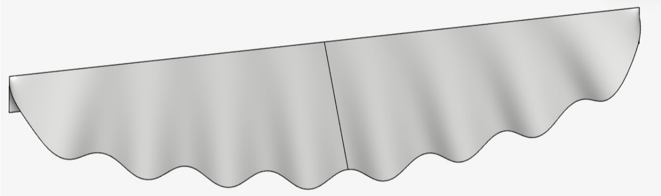

Figure 1. Model of the cuttlefish fin used in the Simscale simulation.

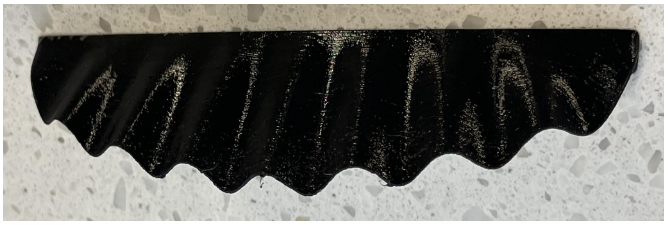

Figure 2. Prototype of the cuttlefish fin additively manufactured.

Figure 3 shows how a direct application of the fin will include rods inserted into the fin while connected to a motor that will allow for movement in the z-axis in a cam-system. Figure 4 showcases the experimental review to determine failure modes and an effects analysis associated with this cam system. Prior to the experimental review there is an evaluation of the material properties, based on the required environmental conditions.

Figure 3. Additively manufactured cam system to hold servo motors.

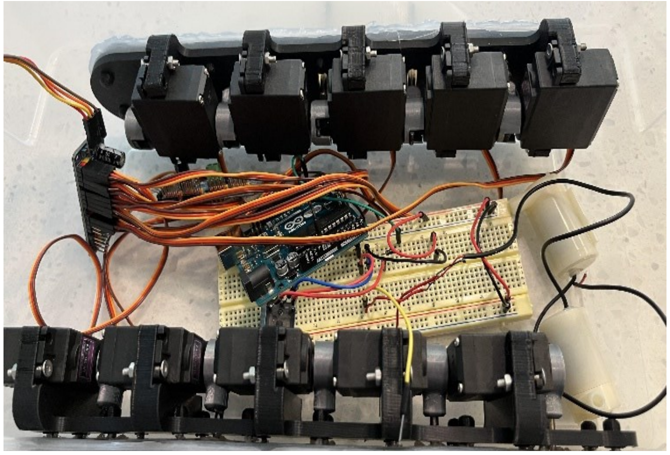

Figure 4. Cam system with servo motors set up in the system.

Environmental Conditions

To ensure that the autonomous vehicle will be able to utilize a fin system successfully, the environmental condition of a wave motion is required from rod to rod within the overall prototype. This is based on two primary swimming behaviors that are showcased in elongated body theory and undulatory swimming mode. In evaluation of the elongated body theory, there is a conclusion that a wave that increases the amplitude down the body is considered laterally symmetric to enable forward motion. Therefore, in the wave's response, the body of the fish is shaped to minimize the lateral recoil from the motion (Singh, 2008). In another consideration, the undulatory swimming mode has longitudinal effects that are clear on the flow separation and which are addressed with a combination of resistive and reactive forces (Singh, 2008). With these considerations of the swimming behaviors, the flexibility within the system based on functionality requirements for the environment were further reviewed for the design.

Of the considerations included for utilization under water, 30 degrees on the positive and negative z-axis for bend profile and reproducibility were identified as key characteristics. Therefore, material strength and flexibility were considered for three main methods of experimental prototypes: resin, thermoplastic polyurethane (TPU), and silicon. Figure 5 shows one of two models that were used for both the resin and TPU additively manufactured designs. Figure 6 show the second of two models used for the silicon method. The rods used in the model for silicon were square instead of round, based on the model that was used to hold the rod in place while the silicon hardened.

Experimental Criteria

The environmental considerations included testing of the method to evaluate the flexibility of its underwater fins, which were made from a silicon-poured material, the Formlabs Flexible 80A resin additively manufactured, and the TPU additively manufactured material. The testing considerations were based on rapid prototyping for resin as well as the additive manufacturing methods (Gupta, 2010). Figure 7 shows that sample preparation for the three prototypes included a dimensional requirement of 30mm x120mm for the fin.

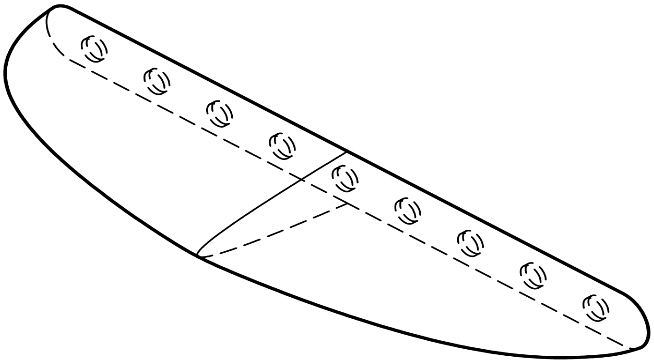

Figure 5. Model of the cuttlefish fin used for resin and TPU additive manufactured designs.

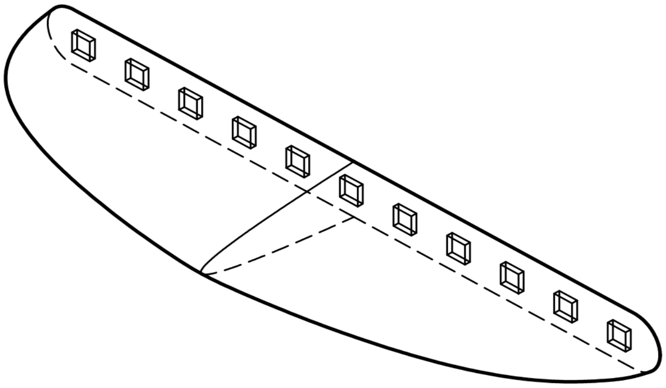

Figure 6. Model of the cuttlefish fin used for the silicon manufacturing method.

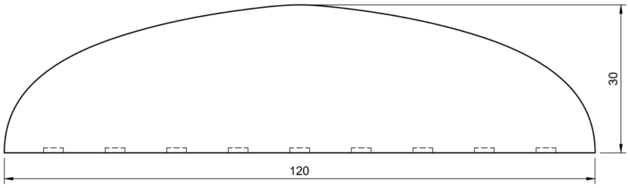

Figure 7. Model of the cuttlefish fin used in the prototypes (side view).

After finalizing the standard dimensions that were utilized in the test, the testing method included qualitative comparison of the three different models. This included the determination of the bending stress and strain of each material, which can be used to compare the flexural strength and modulus of elasticity of each material prior to testing deflection.

Material Process and Properties Overview

To achieve a reliable and performant product, the importance of assessing and recognizing the fabricated fin's tensile strength, elongation percent, and tear strength will determine the robustness of the design. Thermoplastic polyurethane is a linear-segmented block copolymer composed of alternating tough and soft segments. The tougher segments include aromatic or aliphatic diisocyanates, while the soft segments are generally polyols. The mixture of tough and smooth segments contributes to TPU's chemical compound, consisting of exceptional flexibility, abrasion resistance, and mechanical power (American Chemistry Council, 2023). Table 1 shows the averages for comparison against TPU specifications.

Table 1. Thermoplastic polyurethane (TPU) averages.

Shore Hardness Average:	95	Shore A
Tensile Strength Average	35.5	MPa
Elongation at Break Average:	500	%
Tear Strength Average:	80	KN/m

TPU possesses terrific elasticity and resilience, allowing it to recover its original shape after being stretched or deformed. This makes it an excellent choice for objects requiring flexibility and resistance (Covestro AG, 2023). Photopolymer resin includes a liquid base that carries monomers, oligomers, and a photo initiator. When exposed to ultraviolet (UV) light or other appropriate wavelengths of light, the photo initiator activates and initiates a polymerization response, causing the liquid resin to solidify into a single layer. After repeated iterations of this sequence, the machine can form a finalized 3D model. Table 2 shows the averages for comparison against resin specification.

Table 2. Photopolymer resin averages.

Shore Hardness Average:	80	Shore A
Tensile Strength Average	8.76	MPa
Elongation at Break Average:	107.22	%
Tear Strength Average:	22.35	KN/m

Photopolymer resins provide numerous advantages compared to traditional 3D printing methods. Firstly, they allow high-resolution printing with extremely high detail and smooth topological surfaces. The liquid nature of the resin allows for complex geometry to be appropriately reproduced in the printed item. Additionally, photopolymer resins provide super dimensional accuracy, making them appropriate for programs in which unique measurements and tight tolerances are required (3D Systems, 2023).

The last material for review is silicon. When casting silicone items, the process includes a master or primary model that is utilized to create a mold into which the silicone material is poured or injected. Once the silicone cures, the outer mold is removed, leaving the finalized silicone object. This technique is normally used for producing complicated shapes or creating multiple objects from a single casting pattern (Polytek, 2023). Table 3 shows the averages for comparison against silicon specifications.

Table 3. Casting silicon averages.

Shore Hardness Average:	22	Shore A
Tensile Strength Average	4.61	MPa
Elongation at Break Average:	535	%
Tear Strength Average:	22.25	KN/m

Casting silicone offers many benefits. Firstly, it has tremendous flowability, permitting it to penetrate small details and complex geometry within the object. Additionally, casting silicone exhibits high tear strength. This allows the final object to be subject to constant flexing without surface separation or deformation within the model. Moreover, casting silicone possesses chemical resistance, ensuring compatibility with various environmental substances (Polytek, 2023). Tables 1-3 show averages of the key characteristics, such as shore hardness, tensile strength, elongation at break, and tear strength, respectively. Shore A hardness is measured by the intensity of indentation made through a distinct indentation under an exact force. The indenter is mostly a conical or spherical tip, and the force is standardized. The intensity of indentation is then measured, and the result is a Shore A hardness value; a low value representing high flexibility and compressibility, while a high value represents stiffness and a material that is harder to indent (ASTM International - Standards Worldwide, 2021).

The Shore A hardness values for TPU range anywhere from 92 to 98 for stiff polyurethane meant for 3D printing. Table 1 shows that the specific TPU Shore A chosen for the fin prototype was 95, due to its abundancy in the 3D printing sphere and its ease of fabrication on many different machines, due to it being stiffer (RapidMade, 2019; IEMAI, 2023; Ultimaker, 2017; ColorFabb, 2023; Lubrizol, 2018). Table 2 shows that the hardness values for photopolymer resin averaged 80, due to the fact that the resin being used was from materials and SLA company Formlabs. Formlabs had formulated a special photopolymer resin that, when fully cured, is flexible and compressible. Thus, the 80 Shore A hardness is all that was available at the time of conception, though it was still considered stiff. This resin was used specifically as it is one of the only resins available on the market that claims to be flexible while being able to be used with additive manufacturing processes (Lay3rs, 2023; 3DPRINT.ME, 2021; Fast Radius, 2020; Formlabs, 2020;

SyncInnovation, 2020; MLC, 2023; Filament2print, 2023; CTFAssets, 2018; SourceGraphics, 2023). Casting silicone has one of the lowest Shore A hardness values, while not requiring heavy machinery to fabricate. Table 3 shows an average of 22 for Shore A hardness. The silicone was very flexible and could easily be compressed or stretched without any plastic deformation. The fabrication process was unique to the other materials mentioned, as a mold was required to be able to cast the final model. In the case of this specific project, a 3D-printed mold was made from polylactic acid (PLA) and, once assembled, the casting silicone was poured in. After it cured, the mold was taken apart and the final model was released. This material was chosen for its ease of fabrication, high deflection, and compression ranges; plus, the cost to manufacture it was low (Primasil, 2023; Smooth-On, 2019; Norseal, 2018; Renishaw, 2017; Yumpu, 2023; Wacker, 2023).

Material Tensile Strength Overview

The British Plastics Federation (BPF) claims that tensile strength is decided by subjecting a plastic specimen to a controlled tension pressure until it fractures. The pressure applied is divided by the original cross-sectional location of the specimen to calculate the tensile strength. Tensile strength is normally expressed in units per area, including pounds per square inch (psi) or megapascals (MPa) (British Plastics Federation, 2023). Thermoplastic polyurethane tensile strength can range from a low of 17 MPa to a high of 60 MPa, depending on factors such as full material composition, age of the material, density of the final model, and the specific material manufacturer. The information on the specific TPU used in this current project was that it had an average tensile strength of 35.6 MPa. This is high, considering it is an additively manufactured polymer. However, that MPa rating can be assumed due to how stiff the material is (RapidMade, 2019; IEMAI, 2023; Ultimaker, 2017; ColorFabb, 2023; Lubrizol, 2018).

Formlab's photopolymer resin had a very low tensile strength, considering it was also a stiff material. Table 2 shows that the average tensile strength of the Formlabs flexible resin was 8.9 MPa. Ultimately, it was assumed that this was low, due to deviations in the curing process and the material composition of the polymer itself not having very strong covalent bonds (Lay3rs, 2023; 3DPRINT.ME, 2021; Fast Radius, 2020; Formlabs, 2020; SyncInnovation, 2020; MLC, 2023; Filament2print, 2023; CTFAssets, 2018; SourceGraphics, 2023). Casting silicone had the lowest tensile strength of all the materials tested. Table 3 shows that the average tensile strength of casting silicone was 4.6 MPa. This value was deemed accurate after testing and was assumed to be low, due to material casting variables and the specific formulation used, which was a platinum-based or addition system, meaning two parts were added to create the final silicone (Primasil, 2023; Smooth-On, 2019; Norseal, 2018; Renishaw, 2017; Yumpu, 2023; Wacker, 2023).

Material Elongation at Break Overview

The American Society for Testing and Materials defines elongation at break as a way of subjecting a test specimen to tensile forces until it fractures. The elongation is calculated by measuring the change in overall length of the specimen at the point of fracture relative to its original length, and expressing it as a percent (ASTM International - Standards Worldwide, 2022). TPU had a high elongation at break that was not expected. At an average of 500% before failure, this material would be able to endure very high stretching before it would break. In the end, this material was skipped, due to its stiffness. The elongation at break percentage was high, but the overall mechanism was not stretching the fin very much but instead oscillating between a few states (RapidMade, 2019; IEMAI, 2023; Ultimaker, 2017; ColorFabb, 2023; Lubrizol, 2018).

The photopolymer resin, on the other hand, had a low elongation at break. At only 107%, it would not stretch much before cracking or separating. Ultimately, this would not work for the project, as one of the requirements was that the fin stretch and bend regularly. Furthermore, it was also stiffer than originally expected, which resulted in a lower deflection than desired (Lay3rs, 2023; 3DPRINT.ME, 2021; Fast Radius, 2020; Formlabs, 2020; SyncInnovation, 2020; MLC, 2023; Filament2print, 2023; CTFAssets, 2018; SourceGraphics, 2023). The casting silicone had the highest elongation at break of any of the listed materials at an average of 535% before failure. Coupled with its low hardness and high deflection rate, this material ended up with a high ranking as the most suitable material (Primasil, 2023; Smooth-On, 2019; Norseal, 2018; Renishaw, 2017; Yumpu, 2023; Wacker, 2023).

Material Tear Strength Overview

The American Society for Testing and Materials identifies tear strength as subjecting a piece of the specific material to a controlled tearing force. The specimen is normally a small, thin sheet with a standardized cut taken out of the material. The force required to propagate the tear through the specimen is measured, after which tear strength is calculated based on the force per unit thickness (ASTM International - Standards Worldwide, 2020). Table 1 shows that, for TPU, the average tear strength of the material was 80 KN/m. This is high on the scale of tear strength for an additively manufactured material. In fact, out of all the chosen materials, thermoplastic polyurethane had the highest average tear strength. This was most likely due to many factors, such as layer height, print temperature, and material composition (RapidMade, 2019; IEMAI, 2023; Ultimaker, 2017; ColorFabb, 2023; Lubrizol, 2018). The photopolymer resin had, on average, a much lower tear strength at 22.2 KN/m. This is more in line with conventionally manufactured silicone and rubber products. According to SIMTEC, the typical tear strength of solid silicone rubber is 9.8 KN/m; therefore, the Formlabs flexible resin was able to achieve a little over double that. (Lay3rs, 2023; 3DPRINT.ME, 2021; Fast Radius, 2020; Formlabs, 2020; SyncInnovation, 2020; MLC, 2023; Filament2print, 2023; CTFAssets, 2018; SourceGraphics, 2023). In this study, the casting silicone average tear strength was found to be 22.25 KN/m. This was very similar to the photopolymer resin and double that of solid silicone rubber products (Primasil, 2023; Smooth-On, 2019; Norseal, 2018; Renishaw, 2017; Yumpu, 2023; Wacker, 2023).

Testing Process for Material Deflection

In the process of evaluation for material selection, the development of deflection testing was established. This included the following processes after developing testing extrusions required in TPU, resin, and silicon. Figure 8 shows the development and utilization of the material test fixture (MTF). This system utilized a force gauge that measured in pounds (lbs.), zero gauge, and had an added flat-end probe to gauge. Each material extrusion was placed into the MTF with the end with a hole horizontally level to the ground. To measure the force, the end was placed into the MTF cutout with holes on either side. When the material extrusion was set in place and the holes in the fixture were lined up with the holes in the extrusion, a force was applied to the set screws through both sets of holes to secure them tightly. Figure 9 shows the fastener being tight and flush against the MTF wall.

Figure 8. Material test fixture (MTF) shown with material extrusions.

Figure 9. Material test fixture with a material extrusion of TPU.

After the material extrusion's exposed small end was pressed to ensure the gauge probe was pressing against either vertical wall of the material extrusion, a measurement could be taken. Figure 10 show that this measurement was not taken at the top or bottom; instead the gauge face was precisely horizontal along the XY axis to ensure that the most accurate measurements were obtained.

Figure 10. Force gauge position against material extrusions to accurately measure deflection.

To measure deflection, the gauge was held firmly and rotated around the MTF in a counterclockwise direction (gauge on right side of extrusion). The test continued to turn the fixture until the gauge read the desired force, noted as 5 lbs. Once the force was reached, the angle of the material was deflected using the numbered angle readouts inscribed into the fixture. This test was completed for five iterations to showcase an average of the results and identify the optimal material for use. This resulted in an observation of a minimal amount of deflection force, based on the maximum degree of deflection for silicon compared to TPU and resin.

Material Selection

As the experimental criteria were finalized, evaluation of the material properties was used to narrow down prototype options. Additive manufacturing and resin pouring are two popular methods for creating three-dimensional objects, each with their advantages and disadvantages. The three properties considered were accuracy and precision, speed, and complexity. Accuracy and precision evaluations showed that additive manufacturing is generally more accurate and precise than pouring resin. Additive manufacturing required computer-aided-design (CAD) software to create a digital model of the object, which was then printed layer-by-layer using a highly precise nozzle. Pouring resin involves manually pouring the resin into a mold and waiting for it to cure, which can result in inconsistencies in the prototype. The speed evaluation process showed that that during the manufacturing process pouring resin is generally faster than additive manufacturing, because it can be left to cure. However, overall speed for resin was identified to be longer, because the model development also utilized CAD and production of the model cast. The complexity evaluation showed that additive manufacturing was better suited for complex objects with intricate details, based on the CAD creation of complex geometries with ease. Pouring silicon is better suited for simpler objects with fewer details. Figures 11 and 12 show that required flexibility was based on a rod placement of 12.5 mm for additively manufactured fins and 10.5 mm for silicon-poured fins, respectively, for required movement within the prototype fin.

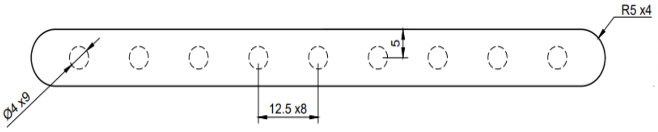

Figure 11. Model of the cuttlefish fin used in additively manufactured prototypes (front view).

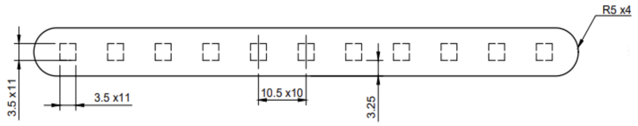

Figure 12. Model of the cuttlefish fin used in silicon-poured prototypes (front view).

Figures 13 and 14 shows that the additively manufactured fins—using the design from Figure 11—had a greater distance, based on the flexural strength for resin (Formlabs, 2022) and TPU (Ultimaker, 2017), respectively.

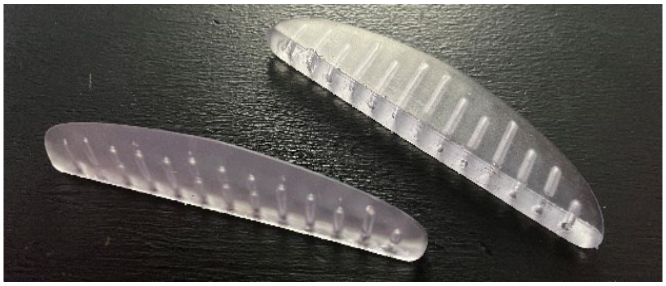

Figure 13. Prototype of resin additively manufactured model.

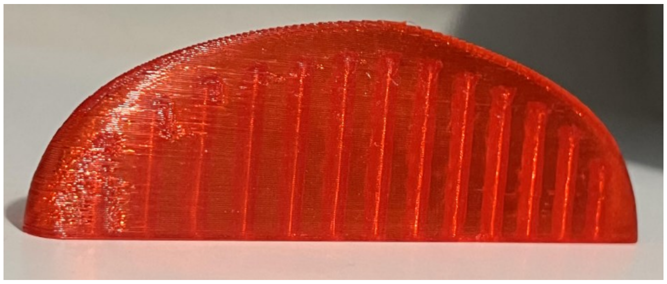

Figure 14. Prototype of TPU additively manufactured model.

The printing details and parameters for the resin model included printing on the Formlabs Form 3 Resin 3D Printer. Figure 13 shows that the model cured well and was fairly flexible and visibly translucent. The rod holes did not empty fully during the curing process, but this was mitigated by forcing the rods through the model, thereby allowing them to function as intended. Printing parameters included the slicer Formlabs Preform (3.22.1). The printer type was Form 3/3+ with material Flexible 80A V1, and a layer thickness of 0.1 mm with default printer settings. The printing details and parameters for the TPU model included printing on the Artillery Sidewinder X1. Printing parameters included the slicer Ultimaker Cura (4.12.1).

This included a layer height of 0.2 mm, a line width of 0.5 mm, a wall count of 1, both top and bottom layers with a count of 3, an infill density of 0%, a printing temperature on the hot end of 230 degrees Celsius, a printing temperature of the build plate of 45 degrees Celsius, a flow rate of 100%, a general print speed of 60 mm/s, a skirt build plate adhesion type, with a skirt line count of 3, and a skirt distance of 5 mm. Figure 15 shows that the silicon pour fin—again using the design from Figure 11—had a shorter distance, based on the flexural strength for silicon (Shin-Etsu, 2005), and was a silicon pour utilizing the cast model shown in Figure 16.

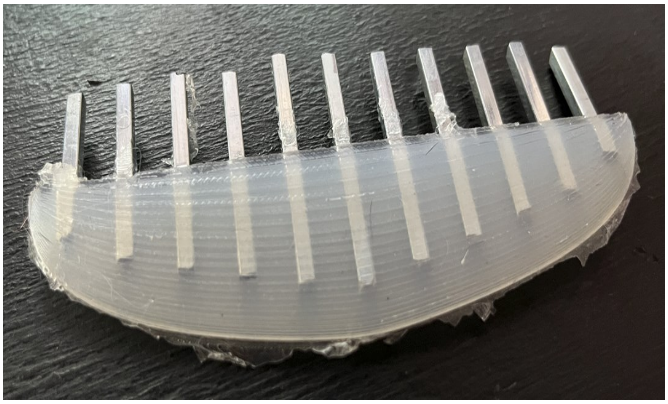

Figure 15. Prototype of the silicon pour method.

Figure 16. Silicon pour prototype cast model.

Ultimately, the casting silicone model was chosen to fabricate the next selection of cuttlefish fins. The high tear strength coupled with its low Shore A hardness, average tensile strength, and high elongation at break made it the most suitable material to move forward with. Furthermore, testing was done to verify these claims. Fabrication of a fin out of TPU, flexible photopolymer resin, and silicone was done to determine the best overall material to continue to fabricate fins out of. In the end, the casting silicone proved to be a fantastic material for fin manufacture for the cuttlefish fin UAV.

Experimental Review of Fin

The qualitative experimental review included the flexibility of the three materials and their chemical structures, specifically the cross-linking density and length of the polymer chains. The flexible 80A resin has properties that have high durometer, compared to other materials on the market, slow spring back, which allows for material to retain bend for longer, and high tensile strength. The TPU has properties that have high abrasion resistance, high shear strength, and high elasticity. Casting silicon has properties that have very low durometer, compresses well, and can be molded onto other objects with ease. Figure 17 shows the process of the manufacturing and testing methods.

The test setup included an evaluation of three different considerations for flexibility. The first consideration of flexibility was point-to-point. Figure 15 shows an example of this bend profile from each neighboring rod. This was considered 17% of the flexibility requirement. The second consideration was a 30-degree, full-bend test of the fin. This was considered 33% of the flexibility requirement. Figure 2 show that the remaining 50% was considered in a sinewave motion. Silicone-poured material has low cross-linking density and long-chain molecules, making it highly flexible and elastic, while Formlabs Flexible 80A resin and TPU 3D printed material have different chemical structures and properties that provide a balance of flexibility and strength. Figure 18 shows the process of bending the fins at 10 degrees of flexibility, where the resin fin broke.

In addition, the silicon-poured material was more flexible than TPU, due to the differences in their chemical structures and manufacturing processes. TPU was composed of alternating hard and soft segments, with the soft segments being responsible for its flexibility. However, the manufacturing process of TPU required a layer-by-layer deposition of the material, which led to a higher cross-linking density compared to silicone. This higher cross-linking density limits the movement of the polymer chains, which makes the material less flexible than silicone (Ultimaker, 2017). Figure 19 shows the process of installing the pins for the point-to-point movement, where movement was limited to within 25% of the bending of the fin.

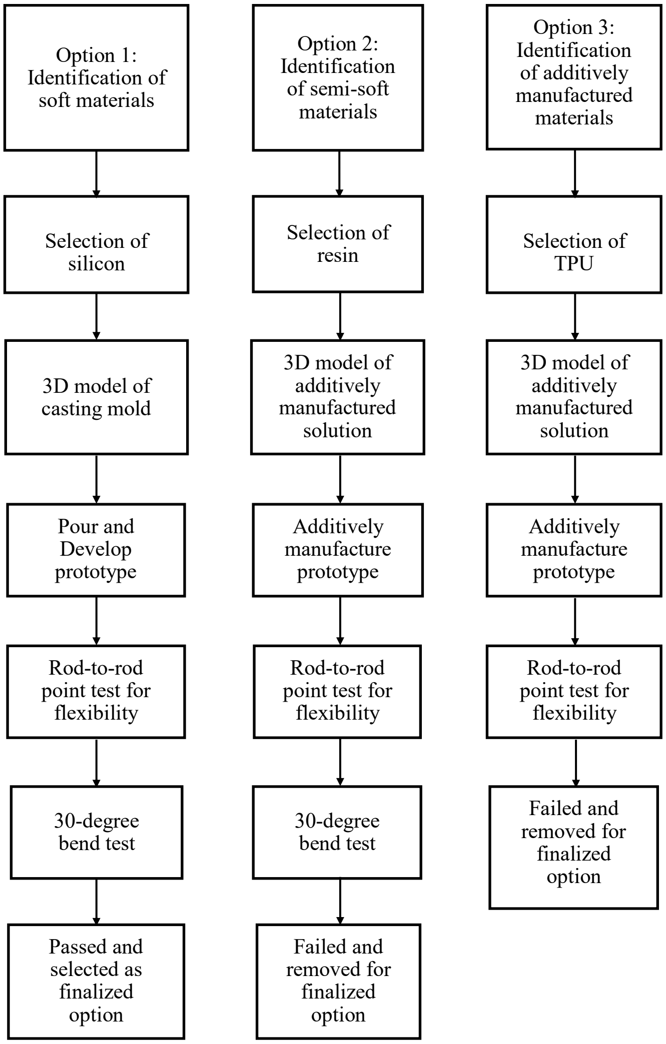

Figure 17. Process of the manufacturing and testing methods.

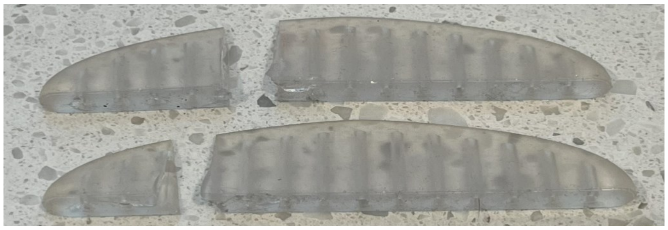

Figure 18. Resin fin post stress testing at 10 degrees of flexibility.

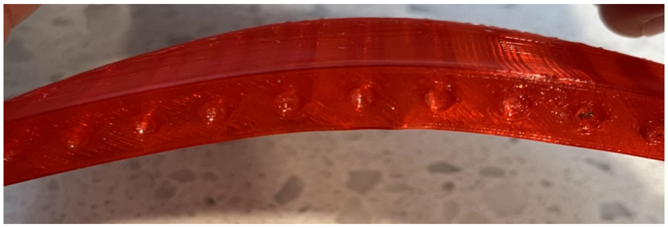

Figure 19. Demonstration of the fin deforming during the bending test within 25% of the TPU fins.

Overview of Fin Malleability

The malleability of the three experimental materials—resin, thermoplastic polyurethane (TPU), and silicon—in the application of a fin that is required to bend at 30 degrees along the positive and negative z-axis to create a wave motion to propel an autonomous underwater vehicle resulted in the identification of an optimal material selection. The resin solution split apart at 33% of the required flexibility at a whole fin evaluation. The TPU solution was able to meet the whole-fin evaluation but, at the point-to-point movement, there was rod slip that limited motion to 83% of the required flexibility. Table 4 shows the test results on which the final prototype was based.

Table 4. Summary of flexibility testing.

Material Selection	Test (% of Flexibility)	Pass/Fail
TPU	Point to Point (17%)	Fail
TPU	End to End (33%)	Pass
TPU	Sine Wave (50%)	Pass
Resin	Point to Point (17%)	Fail
Resin	End to End (33%)	Fail
Resin	Sine Wave (50%)	Fail
Silicon	Point to Point (17%)	Pass
Silicon	End to End (33%)	Pass
Silicon	Sine Wave (50%)	Pass

Conclusions

The overall material properties were determined to play a crucial role in the flexibility requirements to mimic a cuttlefish fin design. In the evaluation of TPU, resin, and silicon materials, the overall considerations included material durometer, print evaluation, and deflection. Table 5 shows the deflection averages with the experimental process and specifications of durometer.

Table 5. Summary of deflection and material specifications.

Material	Material Durometer (Shore A)	Material Usage (g)	Maximum Deflection (XY) (°)	Force at Deflection (lbs.)
TPU	95	9	20.5	4.9-5.1
Resin	80	9	61.5	4.8-5.0
Silicon	22	10	90.0	0.57-0.62

In addition to flexibility by percentage and the average deflection, the solution for the development of a prototype also included material processing and success rate. Table 6 shows the overall averages for the summary of material processing.

Table 6. Summary of material processing.

Material	Processing Time (min)	Processing Time Per Part (min)	Post Processing Time Per Part (min)	Process Success Rate (#/6)
TPU	173	57.7	1.7	6/6
Resin	123	41.0	6.0	4/6
Silicon	1440	480.0	3.3	6/6

These results indicate that silicon was the ideal solution, based on its ability to successfully meet the flexibility criteria without damage to the fin, and preferred from the evaluation criteria. Therefore, the system for the prototype was developed considering these results to have the fins fully submerged with slight movement within the static pool of water to demonstrate any type of forward motion. Figure 20 shows that the material selection provided for the system had the ability to slightly propel the fin with a forward motion based on the fin material and design optimizations.

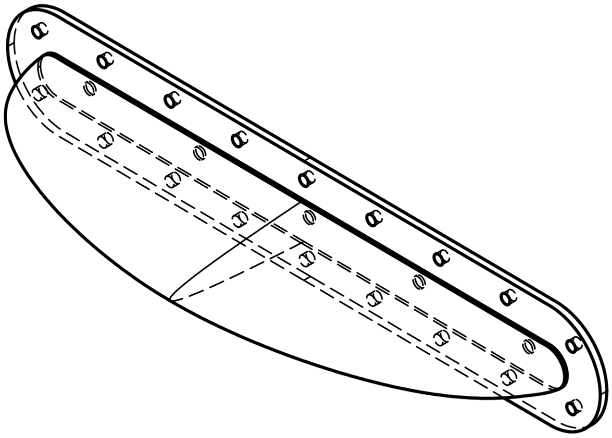

Figure 20. Finalized model for silicon production prototype.

Figure 21 shows the development of the prototype in which slight modifications to the design for fin thickness and size for additional force forward, as well as an extended base to act as a gasket, was used in the production of the prototype.

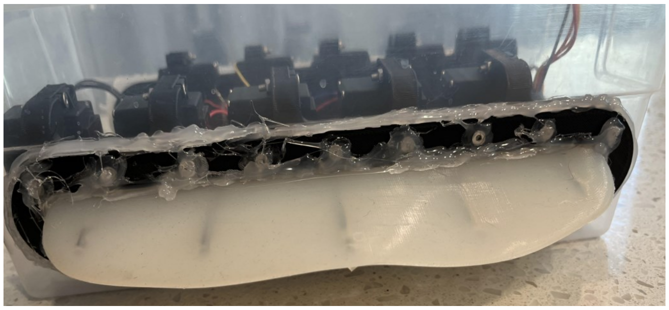

Figure 21. Finalized prototype for silicon production.

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Biographies

KENDRA KIM is an industry professional pursuing a doctorate in systems engineering at Arizona State University. Kendra received her BSE in Electrical Systems Engineering, with a secondary focus in robotics from Arizona State University, and her MS in Systems Engineering. Kendra may be reached at klkim@asu.edu

SANGRAM REDKAR is an associate professor at Arizona State University and works in robotics, dynamical systems, and controls. Dr. Redkar may be reached at sredkar@asu.edu

MAX EDWARD is pursuing a bachelor's degree in digital making and fabrication with a secondary focus in robotics and embedded systems from the University of Advancing Technology. Max has more than six years of experience in the 3D printing industry with a focus in design for additive manufacturing. Max may be reached at maxedwar@uat.edu

ANALYZING ELLIPTICAL DELAMINATION IN QUASI-ISOTROPIC COMPOSITE LAMINATES: A NEW APPROACH

Paul Akangah, North Carolina A&T State University; MA Muktadir, North Carolina A&T State University

Abstract

Composite materials have been used in manufacturing—from small structures to complex structures such as aircraft, ships, and space vehicles—to increase corrosion resistance and decrease weight, when compared to pure materials. During the production process, or during the assembly of the structures, delamination may occur between two layers in different shapes, such as circular, spherical, egg, or elliptical. Such delamination is a common cause of failure in composite laminates of sandwich structures, which can become unstable under different loading conditions. Understanding this instability is essential in designing composite and sandwich structures. In this current study, a literature review was done to develop a description of the effect of delamination in a composite structure, and identify the reasons and solutions depicted in those studies. Finally, as stress and strain are critical factors in determining structural strength, strain and potential energy were calculated from the equations used in those previous studies using a novel algorithm (MATLAB) to analyze the effect of elliptical delamination in a quasi-isotropic composite material. The results were also compared with the previously calculated results produced by the finite element (FE) and Rayleigh-Ritz (R-R) methods.

Introduction

Composite materials are those composed of two or more materials bonded at their interfaces. The region is large enough to be considered continuous. Various materials—such as reinforced rubber and filled polymers, mortars and concrete, alloys, porous and cracked media, fiber composites, and polycrystalline aggregates (metals)—fall into this category (Hashin, 1983). The history of composite materials is not new. Thousands of years ago, mankind used composite materials to reinforce sun-dried mud brick buildings; many of the earliest known civilizations in Mesopotamia at Sumer used straw to reinforce their structures (Campbell, 2010). However, composite materials can now be produced that have advantages over those of competing materials, thanks to advances in polymer chemistry and high-strength man-made fibers. These materials have many advantages, including enhanced strength and stiffness, longer fatigue life, corrosion resistance, and reduced assembly costs by using fewer details and fasteners. Fiber-reinforced composites, especially those with carbon fibers, have higher specific strengths and specific moduli than comparable metal alloys. As a result, vehicles and planes have better performance, greater payloads, and longer range (for vehicles) (Campbell, 2010). Figure 1 shows a buckled sublaminate.

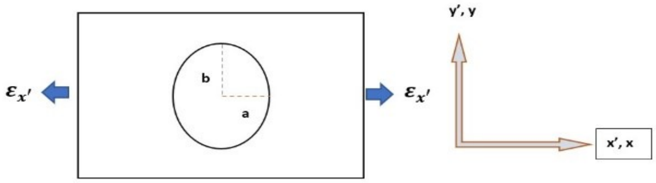
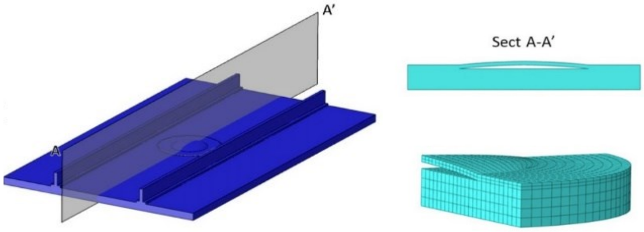


Figure 1. Plan view of a buckled sublaminate.

In addition to aircraft wings and fuselages, automobile body panels, marine deck structures, and carbon fiber-reinforced polymer composites are used for a wide range of advanced structural applications. Compared to conventional aluminum alloys, composites have high specific strength and stiffness. This results in a lighter structure and reduced manufacturing costs. It was reported that a weight reduction of 1 kg in an aircraft structure can save 2,900 liters of fuel annually (Flower & Soutis, 2003). Especially for large engineering structures, such as aircraft and ships, composite structures are increasingly being designed and analyzed. New Boeing and Airbus airliners use a greater proportion of composite materials, resulting in reduced structural weight and improved performance. In helicopters, composites are particularly useful for vibration/noise control. In the design of various types of aircraft, the increased use of composites has become an influential metric. It is possible to design more freely with anisotropic composites than with conventional materials. They have, however, encountered some difficulties in structural analysis, due to the increased number of design parameters. Composite laminated plates that are thin may buckle before reaching their strength limit as shell structures. Engineering structures can buckle in a variety of ways, such as global or local deflections, leading to the collapse of the structure. As a result, structural components must be designed to avoid buckling failures (Xu, Zhao & Qiao, 2013).

In laminated composites, however, delamination is generally recognized as one of the earliest failure modes. The reason for this is the relatively low interlaminar strength. A manufacturing defect or a low-velocity impact could cause delamination (Johar, Wang & Tamin, 2017; Sellitto, Saputo, Damiano, Russo & Riccio, 2019; Soutis, 2005; Turon, Camanho, Costa & Dávila, 2006). Delamination may be of different shapes, strips, rectangles, and ellipses. Figure 2 shows a 3D view of buckling in a sublaminate. In this current study, only the ellipse shape was considered for the new approach to the solution.



(a) 3D view. (b) Local buckling.

Figure 2. Buckling in a sublaminate. Reprinted with permission.

Previous Studies

Delamination of composite panels is one of the most prevalent forms of damage in composite structures, and it can significantly reduce load-carrying capacity when caused by foreign objects or improper manufacturing. There is a risk of delamination cracks growing rapidly under compressive loads, unlike fatigue fractures in metallic materials, which occur under extensional loads (Xu et al., 2013). There is a tendency for composite structures to delaminate, strength and stiffness to decrease, and the lifetime of the structure to be limited. The prevalence of composite materials has caused designers to look for ways to delay or prevent delamination so that the structure's life and load-bearing capability will be increased (Garg, 1988). Among fiber-reinforced composites, delamination is a critical failure mode. Multiple delaminations can result from impact loading, as well as sublaminate buckling, significantly reducing residual compressive strength. Additionally, delamination plays an important role in in-plane failure by joining transverse matrix cracks. In quasi-isotropic laminates loaded in tension at an off-axis angle, a characteristic pattern of edge damage causes large reductions in in-plane strength. Delamination can still result in large strength reductions, even when continuous fibers run in the loading direction, and especially when plies of the same orientation are blocked together (Wisnom, 2012).

Moreover, the reduction of stiffness caused by delaminations reduces the natural frequency, which may cause resonance, if the reduced frequency is close to the working frequency (Della & Shu, 2007). Another reason for delamination is the drilling process, which is a crucial final manufacturing step for composite laminates. In fact, drilling-induced delamination is the most critical failure mode during the drilling of composite laminates, resulting in heavy losses. According to reports, 60% of composite laminates are rejected during final assembly, due to drilling-induced delamination damage (Al-Wandi, Ding & Mo, 2017; Fleischer, Teti, Lanza, Mativenga, Moehring & Caggiano, 2018; Geng et al., 2019; Stone & Krishnamurthy, 1996; Wang, Melly & Li, 2018).

Detecting damage (delamination) and monitoring the health of composite structures are both critical needs and requirements (Zou, Tong & Steven, 2000). Vibration-based model-dependent methods are a promising option for composite structures incorporating piezoelectric sensors and actuators (Zou et al., 2000). In terms of the dynamic response parameters analyzed, these methods can be divided into modal analyses, frequency domain analyses, time domain analyses, and impedance domain analyses. The modal analysis provides information on global and local damage. These methods are relatively easy to use and cost-effective. However, these methods still face many challenges and obstacles before they can be implemented (Zou et al., 2000). Under axial compression or lateral pressure, or even a combination of the two, an exact solution was derived for buckling a circular cylindrical shell with many orthotropic layers and a large number of eccentric stiffeners. Due to the presence of eccentric stiffeners and different layers in the shell, the coupling between bending and extension can be studied using this theory (Jones, 1967).

In another study (Whitney & Leissa, 1969), the authors showed that the governing equations of an anisotropic laminated plate are formulated using the basic assumptions of the thin-plate theory, including nonlinear terms. In addition, there is a closed-form solution for bending, flexural vibration and buckling in laminates that exhibits unavoidable coupling between bending and stretching. Using the Galerkin method, the authors in another study (Chamis, 1969) examined the buckling problem of anisotropic composite plates. A plate was created from particulate or fiber-reinforced composite material, simply supported, and subjected to a combination of uniform membrane loads. This current study was conducted to determine whether various coupling responses affect the buckling load of a plate and how the buckling interaction equation can be applied in different situations. The Galerkin method is an effective algorithm for solving differential equations, and it can also be used to establish an eigenvalue problem for linear buckling analysis. Finite strip methods (FSM) are also being investigated as efficient methods to predict buckling loads. One of the most commonly used theories for the approximation of buckling analysis is the Rayleigh-Ritz method, based on the theory of energy variational. Choosing an appropriate displacement shape function is crucial for this method in order to properly describe the deflection of the plate in its buckled state, while simultaneously satisfying the boundary conditions (Xu et al., 2013). Using the Rayleigh-Ritz method, the following methodology sections describe the solution using MATLAB.

Methodology

A numerical calculation was performed using the MATLAB algorithm, constituting a novel approach to solving the problem. The strain energy of the sublaminate can be written as Equation 1 (Ashton & Whitney, 1970; Shivakumar & Whitcomb, 1985):

$$U=\frac{1}{2}\cdot\int_{-a}^{a}\int_{-b}^{b}\left\{D_{11}\left(\frac{\partial^2 w}{\partial x^2}\right)^2+D_{22}\left(\frac{\partial^2 w}{\partial y^2}\right)^2+2D_{12}\left(\frac{\partial^2 w}{\partial x^2}\right)\cdot\left(\frac{\partial^2 w}{\partial y^2}\right)+\right.$$
$$\left.4D_{66}\left(\frac{\partial^2 w}{\partial x\cdot\partial y}\right)^2+4D_{16}\left(\frac{\partial^2 w}{\partial x^2}\right)\cdot\left(\frac{\partial^2 w}{\partial x\cdot\partial y}\right)+D_{26}\left(\frac{\partial^2 w}{\partial y^2}\right)\cdot\left(\frac{\partial^2 w}{\partial x\cdot\partial y}\right)\right\}dA \tag{1}$$

where,

$$w=\left[1-\left(\frac{x}{a}\right)^2-\left(\frac{x}{b}\right)^2\right]^2\cdot\left\{C_0+C_1\left(\frac{x}{a}\right)^2+C_2\left(\frac{x}{b}\right)^2\right\}$$

a = half-length of an elliptical sublaminate – [m]
b = half-width of an elliptical sublaminate – [m]
w = transverse (in the z-direction) deflection – [m]
D's = flexural stiffness coefficients of the sublaminate – [N/m]
C_0 = generalized displacement – [m]
C_1 = generalized displacement – [m^{-1}]
C_2 = generalized displacement – [m^{-1}]
θ = angle between x and x' axes – [degree]
v = Poisson's ratio of the laminate
A's = in-plane stiffness coefficients of the sublaminate – [N/m]

N_x, N_y, N_{xy} = sublaminate stress resultants – [N/m]
ε_x, ε_y, ε_{xy} = sublaminate strain
x-y-z = sublaminate cartesian coordinate system
x'-y'-z' = base laminate cartesian coordinate system

For an ellipse, $dA = \pi \cdot dx \cdot dy$, hence Equation 1 (strain energy) can be written as Equation 2:

$$U=\frac{\pi}{2}\cdot\int_{-a}^{a}\int_{-b}^{b}\left\{D_{11}\left(\frac{\partial^2 w}{\partial x^2}\right)^2+D_{22}\left(\frac{\partial^2 w}{\partial y^2}\right)^2+2D_{12}\left(\frac{\partial^2 w}{\partial x^2}\right)\cdot\left(\frac{\partial^2 w}{\partial y^2}\right)+\right.$$
$$\left.4D_{66}\left(\frac{\partial^2 w}{\partial x\cdot\partial y}\right)^2\right\}dx\cdot dy \tag{2}$$

Transfer the coordinate system into non-dimensionless coordinates was done by setting the following:

$$\frac{x}{a}=\varsigma\rightarrow x=a\varsigma$$
$$dx=ad\varsigma$$
$$\frac{dw}{dx}=\frac{dw}{ad\varsigma}$$
$$\frac{d^2w}{dx^2}=\frac{1}{a^2}\cdot\left(\frac{d^2w}{d\varsigma^2}\right)$$

Similarly, by setting $y = b\eta$,

$$\frac{dw}{dy}=\frac{dw}{bd\eta}$$
$$\frac{d^2w}{dy^2}=\frac{1}{b^2}\cdot\left(\frac{d^2w}{d\eta^2}\right)$$

Equation 2 (strain energy) can now be written into non-dimensionless coordinates, as given by Equation 3:

$$U=\frac{\pi}{2}\cdot\int_{-1}^{1}\int_{-1}^{1}\left\{D_{11}\frac{1}{a^4}\left(\frac{\partial^2 w}{\partial\varsigma^2}\right)^2+D_{22}\frac{1}{b^4}\left(\frac{\partial^2 w}{\partial\eta^2}\right)+2D_{12}\frac{1}{a^2\cdot b^2}\left(\frac{\partial^2 w}{\partial\varsigma^2}\right)\cdot\left(\frac{\partial^2 w}{\partial\eta^2}\right)+\right.$$
$$\left.4D_{66}\frac{1}{a^2\cdot b^2}\left(\frac{\partial^2 w}{\partial\varsigma\cdot\partial\eta}\right)^2\right\}a\cdot b\cdot d\varsigma\cdot d\eta \tag{3}$$

For a 1-term solution, transverse deflection w can be written using Equation 4:

$$w=\left[1-\varsigma^2-\eta^2\right]^2\cdot\left\{C_0\right\} \tag{4}$$

Using MATLAB, from Equations 3 and 4, strain energy U can be defined by Equation 5:

$$U=\left[C\right]^T\left[K\right]\cdot\left[C\right] \tag{5}$$

where, $[C]^T = \{C_0\}$ and K is the stiffness matrix:

$$\left[K\right]=D_{11}\left[K_1\right]+D_{22}\left[K_2\right]+2D_{12}\left[K_{12}\right]+4D_{66}\left[K_{66}\right]$$

and where, $\left[K_1\right]=\frac{b\pi}{a^3}[10.67],\left[K_2\right]=\frac{a\pi}{b^3}[10.67]$,

$\left[K_{12}\right]=\frac{\pi}{ab}[41.24]$, and $\left[K_{66}\right]=\frac{\pi}{ab}[56.89]$

Now, the potential energy of applied loads can be written as Equation 6 (Ashton & Whitney, 1970; Shivakumar & Whitcomb, 1985):

$$V=\frac{1}{2}\int_{-a}^{a}\int_{-b}^{b}\left[N_x\left(w_x\right)^2+N_y\left(w_y\right)^2+2N_{xy}\left(w_x\cdot w_y\right)\right]\cdot dx\cdot dy \tag{6}$$

where,

$$N_x=A_{11}\varepsilon_x+A_{12}\varepsilon_y+A_{16}\varepsilon_{xy}$$
$$N_y=A_{12}\varepsilon_x+A_{22}\varepsilon_y+A_{26}\varepsilon_{xy}$$
$$N_{xy}=A_{16}\varepsilon_x+A_{26}\varepsilon_y+A_{66}\varepsilon_{xy}$$
$$\varepsilon_x=\left(\cos^2\theta-v\sin^2\theta\right)\varepsilon_{x'}$$
$$\varepsilon_y=\left(\sin^2\theta-v\cos^2\theta\right)\varepsilon_{x'}$$
$$\varepsilon_{xy}=-\left(1+v\right)\sin2\theta\cdot\varepsilon_{x'}$$

If considered, $\theta = 90$ degrees:

$$\varepsilon_x=\left(-v\right)\varepsilon_{x'}$$
$$\varepsilon_y=\varepsilon_{x'}$$
$$\varepsilon_{xy}=0$$

For ellipse, $dA = \pi \cdot dx \cdot dy$, and substituting, $x = a\varsigma$ and $y = b\eta$,

$$\frac{dw}{dx}=\frac{dw}{ad\varsigma}$$
$$\frac{dw}{dy}=\frac{dw}{bd\eta}$$

And, potential energy can be written as Equation 7:

$$V = \frac{\pi}{2} \cdot \int_{-1}^{1} \int_{-1}^{1} \left\{ N_x \frac{1}{a^2} \left(\frac{\partial w}{\partial \varsigma} \right)^2 + N_y \frac{1}{b^2} \left(\frac{\partial w}{\partial \eta} \right)^2 + 2N_{xy} \frac{1}{ab} \left(\frac{\partial w}{\partial \varsigma} \right) \cdot \left(\frac{\partial w}{\partial \eta} \right) \right\} a \cdot b \cdot d\varsigma \cdot d\eta \tag{7}$$

For a 1-term solution, transverse deflection w can be written as Equation 8:

$$w = \left[1 - \varsigma^2 - \eta^2 \right]^2 \cdot \left\{ C_0 \right\} \tag{8}$$

Using MATLAB, from Equations 7 and 8, potential energy can be defined by Equation 9:

$$V = \left[C \right]^T \left[K_V \right] \left[C \right] \varepsilon_{x'} \tag{9}$$

where, $[C]^T = \{C_0\}$ and K_V is the stiffness matrix:

$$K_V = K_{V1} + K_{V2}$$

$$\left[K_{V1} \right] = \frac{b\pi}{a} \left(A_{12} - A_{11} v \right) [1.73]$$

$$\left[K_{V2} \right] = \frac{a\pi}{b} \left(A_{22} - A_{12} v \right) [1.73]$$

Total potential energy is the sum of the strain energy, U, and potential energy, V. Adding Equations 5 and 9, the total potential energy can be defined by Equation 10:

$$\Pi = U + V \tag{10}$$

Using MATLAB and applying the Trefftz criterion (Dym & Shames, 1973), and after differentiating the potential energy, Equation 10 with respect to C_O (two times) yields Equation 11:

$$\left[K \right] + \left[K_V \right] \varepsilon_{x'} = 0 \tag{11}$$

Here, $\varepsilon_{x'}$ is the 1-term buckling strain, the final form for which is given by Equation 12:

$$\varepsilon_{x'} = (-) \frac{[K]}{[K_V]} \tag{12}$$

$$\varepsilon_{x'} = (-) \frac{D_{11}[K_1] + D_{22}[K_2] + 2D_{12}[K_{12}] + 4D_{66}[K_{66}]}{[K_{V1}] + [K_{V2}]}$$

$$\varepsilon_{x'} = (-) \frac{D_{11} \frac{b\pi}{a^3}[10.67] + D_{22} \frac{a\pi}{b^3}[10.67] + 2D_{12} \frac{\pi}{ab}[41.24] + 4D_{66} \frac{\pi}{ab}[56.89]}{\frac{b\pi}{a}\left(A_{12} - A_{11} v \right)[1.73] + \frac{a\pi}{b}\left(A_{22} - A_{12} v \right)[1.73]}$$

$$\varepsilon_{x'} = (-) \frac{D_{11} \frac{b}{a^3}[10.67] + D_{22} \frac{a}{b^3}[10.67] + 2D_{12} \frac{1}{ab}[41.24] + 4D_{66} \frac{1}{ab}[56.89]}{\frac{b}{a}\left(A_{12} - A_{11} v \right)[1.73] + \frac{a}{b}\left(A_{22} - A_{12} v \right)[1.73]}$$

Results and Discussion

Equation 12 is the final equation for this study. Now consider the following data: a plot was drawn using MATLAB to check the buckling strain by changing the width of b. Figure 3 shows the decreasing trend in strain, while increasing the width of b.

b = 25 mm to 150 mm (range)
a = 25.4 mm
E = 68.95 GPa (Aluminium)
v = 0.31
$D_{11} = \frac{h^3}{12} \frac{E}{\left(1 - v^2\right)}$; h = 0.51 mm
$D_{22} = D_{11}$
$D_{12} = vD_{11}$
$D_{66} = \frac{(1 - v)}{2} D_{11}$
$A_{11} = \frac{Eh}{\left(1 - v^2\right)}$
$A_{12} = vA_{11}$
$A_{22} = A_{11}$

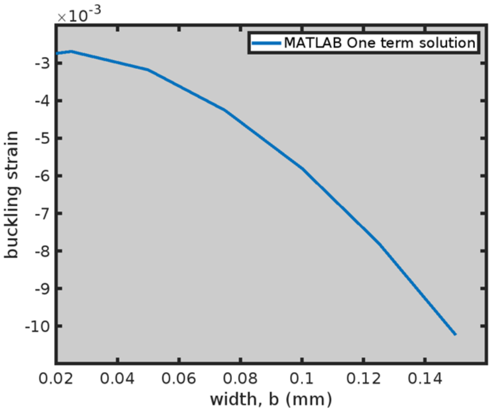


Figure 3. Buckling strain versus width of aluminum sublaminate.

Conclusions and Future Work

This study focused mainly on elliptical, 90-degree sub-laminate buckling strain solutions for considering the 1-term solution. Results might be different, if 3- and 6-term solutions are considered. Results showed different tread compared to the solution done by the same Rayleigh-Ritz method. Finite element analysis can be used to numerically calculate different systems, for example, beam analysis (Hasan, Muktadir & Alam, 2022; Muktadir, Akangah & Yi, 2021a; Muktadir, Akangah & Yi, 2021b). In the future, the finite element approach will be considered to compare the results. As a novel algorithm has now been developed, this study will be continued under the following conditions.

1. FE analyses with ANSYS will be done to compare the results. In that analysis, the effect of material changes will also be analyzed.
2. Two- and 3-term solutions will be completed and compared with the FE analyses.

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Biographies

PAUL AKANGAH is a Teaching Associate Professor of Mechanical Engineering at North Carolina A&T State University. He earned his BS degree from Kwame Nkrumah University of Science & Technology (Kumasi, Ghana), MS in energy engineering in 2005 from the Royal Institute of Technology (Stockholm, Sweden), and PhD in mechanical engineering in 2011 from North Carolina A&T State University. Dr. Akangah's interests include engineering pedagogy, metallic forms for structural and thermal applications, and advanced composites materials. Dr. Akangah may be reached at pmakanga@ncat.edu

MA MUKTADIR is pursuing his PhD in Mechanical Engineering at North Carolina A&T State University. His research interests include robotics, finite element analysis, mechanical design, machine learning, image processing, and additive manufacturing. Mr. Muktadir may be reached at mmuktadir@aggies.ncat.edu

FRAMEWORK FOR THE ANALYSIS OF QUALITATIVE DATA FOR CONSTRUCTION AND ENGINEERING DISCIPLINES: A CASE OF FACULTY PERSPECTIVE DURING COVID-19

Tulio Sulbaran, The University of Texas at San Antonio; Sandeep Langar, The University of Texas at San Antonio;
Sanjeev Adhikari, Kennesaw State University; Rachel Mosier, Oklahoma State University

Abstract

Qualitative research involves collecting and analyzing textual data and provides an opportunity to gain a deeper understanding of a phenomenon, group, or impact. However, the use of qualitative analysis in construction and engineering disciplines has been done with mixed results regarding replicability and rigor. This challenge in using qualitative analyses could be attributed to multiple reasons, including lack of formal qualitative analysis education, fragmented social sciences literature related to qualitative analysis, the time required to conduct such an analysis, construction, and the engineering researcher's lack of understanding of computer science algorithms to analyze textual data. Thus, in this paper, the authors presents a framework to assist construction and engineering researchers in performing qualitative analyses. The framework is also demonstrated through an illustrative example case study. The illustrative example case study uses the responses of 337 educators within the U.S. regarding concerns about online class delivery during the first year of the covid-19 pandemic. The qualitative data were collected using an online survey with open-ended questions allowing respondents to describe their concerns without pre-established options. For the textual analysis, date were collected through an online survey that illustrated the proposed framework. The resulting framework contributes to the body of knowledge through the scholarship of integration by synthesizing the knowledge across two disciplines (social science and computer science) for researchers in the construction and engineering disciplines with an innovative framework that is unbiased, rigorous, and replicable to benefit society.

Introduction

Qualitative research focuses on exploring a subject without complete prior formulations (hypotheses) and is defined as the systematic collection, organization, and interpretation of textual material (Grossoehme, 2014; Malterud, 2001; Borrego, Douglas & Amelink, 2009) and works best for developing new ideas (Harrison, Lin, Carroll & Carley, 2007) to gain a detailed understanding of a phenomenon, group, impact, etc., and to explore patterns within social constructs (Grossoehme, 2014; Malterud, 2001). Many qualitative studies use nominal data to describe groups' perceptions in order to investigate aspects of their world (Fellows & Liu, 2015). Qualitative research methods are more appropriate than quantitative methods in fostering the development of new ideas, as qualitative methods do not require hypothesis testing typically used in mature disciplines/domains (Fellows & Liu, 2015).

Qualitative research can be complex, intimidating (Pratt, Sonenshein & Feldman, 2022), iterative (Charmaz, 2014; Locke, 2001), and identified as time-consuming and costly (Bengtsson, 2016). As per Borrego, Douglas, and Amelink (2009), it is easy to confuse qualitative research methods as being more accessible or less rigorous to perform than quantitative research methods (Hoaglin, Light, McPeek, Mosteller & Stoto, 1982; Koro-Ljungberg & Douglas, 2008). Executing a worthwhile research project using qualitative methods can be more intellectually demanding than quantitative research methodologies (Fellows & Liu, 2015) supported by various software options. Qualitative research is more complicated (than quantitative research) and requires more guidance (Bairagi & Munot, 2019). Without such guidance (such as the framework presented in this paper), selecting the most appropriate qualitative analysis method can be challenging, which can limit theoretical, practical (Spearing, Bakchan, Hamlet, Stephens, Kaminsky & Faust, 2022), and intellectual contributions.

Despite the challenges with implementing qualitative analysis methods, there is a research need to utilize these methods to describe challenges within architecture, engineering, and construction (AEC) (Spearing et al., 2022). Qualitative analysis methods have been used to explore a variety of socio-technical challenges across a range of various construction and engineering topics, such as workplace dynamics (Brockman, 2014), project delivery during the emergency response (Kosonen & Kim, 2018), mega construction projects (Erol, Dikmen, Atasoy & Birgonul, 2020), and the impact of contracts on information management (Celoza, de Oliveira & Leite, 2022) among others (Spearing et al., 2022). In construction, fuzzy-set qualitative comparative analysis has also been utilized (Guo, Lu & Fang, 2022; Ma & Fu, 2020). Furthermore, medical researchers and social scientists utilize qualitative analysis when researching the construction and engineering field (Somerset, Evans & Blake, 2021; Koro-Ljungberg & Douglas, 2008).

Qualitative research has been published extensively in social science. Unfortunately, the social science qualitative analysis research literature is very fragmented. Furthermore, transferring social science analysis methods into construction and engineering research can be challenging (Koch, Paavola & Buhl, 2019). Construction and engineering researchers are not typically trained using the same methods as social scientists with limited formal training in qualitative research (Kelly & Bowe, 2011; Toole, 2007). Furthermore, it can be challenging for construction and engineering researchers to transfer the qualitative analysis methods from the social sciences context into the construction and engineering disciplines (Szajnfarber & Gralla, 2017). In addition, bias still exists in research and research design, and is difficult to identify and remove (Smith & Noble, 2014).

Many analysis methods are used to conduct high-quality qualitative research (Williams, 2007; Pratt et al., 2022). However, the construction and engineering literature lacks resources on qualitative analysis method selection and application, specifically considering the construction and engineering disciplines (Spearing et al., 2022). Challenges in the implementation of qualitative methods to construction and engineering research likely persists due to the dearth of resources (again, such as the one presented in this paper) that support construction and engineering research to use qualitative analysis methods to perform quality research (Spearing et al., 2022). Furthermore, qualitative analysis methods have been used incorrectly in numerous fields (Braun & Clarke, 2006). Misapplications of the method are also evident in architecture, where it is employed to define construction terminology instead of being utilized as an analytical approach (Radhakrishnan, Shanthi Priya, Nagan & Sundarraja, 2011; Dili, Naseer & Varghese, 2010).

Consequently, this current research technique tackles challenges identified in the literature with the time-intensive nature, replicability, and rigor that construction and engineering researchers face in qualitative analyses by introducing a framework that aids them in conducting such analyses. This framework is founded on the principles of social sciences in qualitative analysis and the application of natural language processing algorithms from computer science. To the authors' knowledge, this is the first paper that implements the scholarship of integration to incorporate social sciences and computer science to propose a framework for the construction and engineering discipline to help elevate research quality and bridge the knowledge gap.

The scholarship of integration establishes connections across multiple disciplines (in this research, the social sciences and computer science) and places the specialties in a larger context (in this case, construction and engineering disciplines) to illuminate data in a revealing way (in this case, textual data) (Ream, Braxton, Boyer & Moser 2015). In the section titled Qualitative Analysis Methods, the authors synthesize the fragmented social sciences literature related to qualitative analysis. In the section titled Research Methodology, the authors describe the methodology used to integrate social science knowledge on qualitative analysis and the computer science natural language processing algorithm to develop the framework. Also covered in this section is the illustrative case study as a mechanism to demonstrate the framework in a tangible construction and engineering qualitative analysis. In the following section, Resulting Framework, the authors describe the complete integration of all the framework elements.

Qualitative Analysis Methods

Social science indicates that qualitative research is pluralistic (Corbin & Strauss, 2008; Creswell, 1998). Figure 1 shows how it encompasses many approaches—such as action research, ethnography, ground theory, narrative research, and phenomenological research—uses various data collection devices—such as focus groups, interviews, observations, and secondary data research—and employs multiple data analysis methods—such as content analysis, conversation discourse analysis, grounded theory analysis, narrative analysis, and thematic analysis.

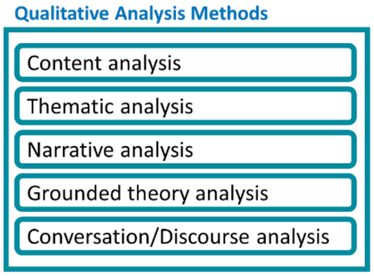


Figure 1. Qualitative analysis methods.

Content Analysis (Deductive and Inductive)

Qualitative content analysis is a method for systematically describing the meaning of qualitative data (Mayring, 2000; Schreier, 2012). The content analysis makes inferences by objectively and systematically identifying specified characteristics of the data. Each characteristic of interest is typically formalized as a coding category (Franzosi, 2004) and is accomplished by assigning successive parts of the material to the categories of a coding frame (Schreier, 2012). This content analysis is performed interactively by cycling through the data repeatedly until finding an optimal result. Qualitative content analysis is considered flexible, because the coding frame is always connected to the data (Schreier, 2012), describing and categorizing shared or common concepts, ideas, and phrases in qualitative data. Content analysis analyzes text using both deductive and inductive methods (Hsieh & Shannon, 2005; Rosengren, 1981).

- Deductive: Coding (or classification) utilizes previously identified context of the features from established sources and utilizes the general context in the data to obtain knowledge about the study along with specific phenomena of the study (Reichertz, 2014). Essentially, the established coding source is used as a baseline comparison for the new data set to develop new knowledge. Deduction interprets the world "from above" or "top-down" within a pre-existing coding system (Reichertz, 2014; Braun & Clarke, 2006). The deduction is handicapped, as it begins with a valid pre-existing coding and belief that the phenomenon's behavior can be predicted (Reichertz, 2014). Deductive content analysis is useful, if the study tests an existing theory in different contexts, such as time, situations, and others (Elo & Kyngäs, 2008).

- Inductive: Coding (or classification) is achieved by assembling certain qualitative features of the information collected, so that this combination of features resembles another in essential points (Reichertz, 2014). Inductive inferences are a tenuous attempt to evaluate the individual parts of the unique concepts of the collected information and determine a coding system. Induction has a viewpoint "from below" or "bottom-up," while searching for a system of coding. Induction is handicapped by not being able to begin from a pre-existing coding and having to consider all the data as unique (Reichertz, 2014). Inductive content analysis is used when there is limited or fragmented research for analyzing a phenomenon (Elo & Kyngäs, 2008).

Thematic Analysis

Thematic analysis involves reading and re-reading data collected, such as interview transcripts or focus groups, and identifying patterns based on meaning in the data in order to identify themes (Braun & Clarke, 2006). This is performed through an active process of reflection, wherein the subjective experience of the researcher is central to identifying data patterns or meaning (Braun & Clarke, 2006). Thematic analysis can be used in a variety of fields, including construction and engineering. Thematic analysis is flexible and allows the generation of new insights derived from the qualitative data (Dovetail, 2023). On the other hand, a flexible approach provides many ways to interpret data patterns or meanings by which patterns in the data might be overlooked. Since the thematic analysis does not utilize an existing theoretical framework, it could limit the interpretive power of the analysis (Braun & Clarke, 2006). However, thematic analysis can help to identify patterns and themes in qualitative data (Bhandari, 2023).

Narrative Analysis

Narrative analysis involves working with narratives to identify different and sometimes contradictory layers of meaning (Esin, Fathi & Squire, 2014). This qualitative analysis is grounded on the syntactic makeup, the clause and its lexica, as the basic analytic unit. Narrative analysis assumes that connecting clauses cohesively follows the language-specific practices and norms of cohesion building (Cooper, 2012). However, narrative analysis is not straightforward, as assumptions about the individual, language, and narrative are incorporated. Therefore, care is required for multiple elements, such as context, place, and time (Phibbs, 2008). Paying attention to how the narrative is constructed and understanding its meaning is vital during analysis. Narrative analysis can be used to describe the content, design, and structure of a dataset. Narrative analysis opens the door for research across multiple disciplines.

Ground Theory Analysis

Ground theory analysis aims to develop a theory inductively about a phenomenon of interest. Grounded theory is a complex and iterative process (Acharyya & Bhattacharya, 2020) with no starting hypothesis. Instead, the hypotheses are built through observations of the dataset and not preconceived ideas (Smith & Davies, 2010). Observations are iteratively compared, emerging patterns are noted and coded, and thematic categories are generated. Additional data collection is utilized to refine initial categories. Data collection continues until no new codes are identified and categories stabilize. These categories form the basis of a theory that can be tested in different settings (Smith & Davies, 2010). The two key terms in grounded theory are: 1) saturation—the point beyond which further exploration yields no new insight, and 2) axial coding—the systematic exploration of relationships amongst categories (Acharyya & Bhattacharya, 2020). The method is said to be grounded because the classification and interpretation of data begin with the data itself rather than from a pre-existing conceptual framework. The method is considered theory because it seeks to model the relationships between the categories that have been generated from the data (Acharyya & Bhattacharya, 2020). The main point of contention in grounded theory is the induction assumption, which states that a theory can be built from the ground up rather than using the more common research approach of a top-down model in which theory leads research design and/or questions.

Conversation or Discourse Analysis

Qualitative conversation or discourse analysis is a method that focuses on individual communications within a group to produce orderly social interaction (Silverman, 2001), assuming conversation is socially structured (Smith & Davies, 2010). Such research focuses on understanding the context through very detailed transcriptions of conversation datasets (Babbie, 2004). Conversation or discourse analysis can be used "to study communication and how language is used to achieve effects in specific contexts" (Bhandari, 2023).

Iterative Qualitative Analysis

It is essential to highlight that all of these qualitative data analysis methods are iterative (Schreier, 2014), requiring repeatedly going through their particular steps, modifying them, and generating subsequent steps. This presents a replicability challenge to construction and engineering researchers, especially without a framework such as the one presented in this paper.

Figure 2 shows the three main iterative steps of qualitative analyses: Describe; Classify/Coding; and, Connect. These three main steps are the foundation of the framework presented in this paper. This allows construction and engineering researchers to benefit from this framework, while having the flexibility to implement any data analysis method—content analysis, conversation discourse analysis, grounded theory analysis, narrative analysis, and thematic analysis—based on the source of the textual data and the research intent. It is also important to highlight that the framework assists construction and engineering researchers and gives them complete control over interpretation of the analysis and its results.

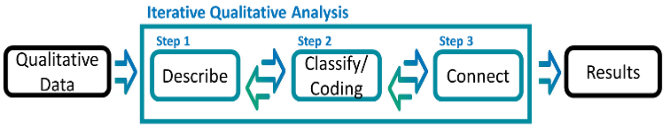


Figure 2. Main steps of qualitative analysis.

The following is a description of the three main steps of the iterative qualitative analysis used in the creation of the framework.

- Describe: The first step in a qualitative analysis is to develop a complete picture or account of the study phenomena. During this first step, the researcher outlines, in words, characteristics of the information collected (Dey, 1993). This phenomenological representation is known as a “thick” description (Geerz, 1973; Denzin, 1978). A “thin” description merely states the facts, whereas a thick description includes characteristics and context of the information, its intentions, and the process (Denzin, 1978). Figure 3 shows the context of the information refers to the event and the cultural or social circumstance (or significance) related to the data; the intention refers to the aim of the data; and, the process relates to the action in which the data are participating.

Figure 3. Thick description.

- Classify or Coding: The second step in a qualitative analysis is to organize, through categories, the information collected in the study about the phenomena. Classifying or coding involves fragmenting and categorizing the information to form explanations and comprehensive themes (Creswell, 2012). During this second step, the researcher must cut into pieces the seamless sequence of information collected (Dey, 1993). Figure 4 shows how these pieces will then be organized based on standard and relevant characteristics forming categories.

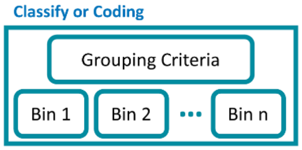


Figure 4. Information categorization.

- Connect: The third step in qualitative analysis is to identify patterns that emerge from the information about the phenomena. The description and classification/coding are not a final determination; rather, they function to analyze the data. During this third step, the researcher identifies the associations among the classified information (Dey, 1993). The researcher can facilitate the identification of associations and/or patterns in the data by analyzing the frequencies with which characteristics occur. Figure 5 shows that the researcher can also tabulate the relationships between different characteristics using quantitative statistical analyses (Dey, 1993). This provides a means for identifying or confirming regularities and variations of connections among the information analyzed.

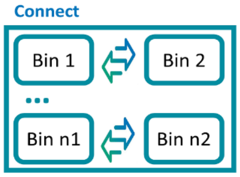


Figure 5. Information categorization.

Research Methodology

This current research study was conducted on the boundaries where multiple disciplines converge—scholarship of integration (Ream et al., 2015). More specifically, the research links the boundaries of social sciences knowledge of qualitative analysis and computer science natural language processing and places them in a construction and engineering context. Therefore, an exploratory mixed research method design was implemented (Clark, Huddleston-Casas, Churchill, Green & Garrett, 2008). This current research method is also characterized by making inferences, in this case from the social sciences and computer science to apply in construction and engineering qualitative research. The exploratory mixed research method was chosen because it is characterized by trying to answer the question of How? In this current study, the “How” was the development of a framework grounded on the social sciences and computer science that the construction and engineering disciplines could use.

The mixed research method design was implemented in three phases: 1) foundation and existing knowledge; 2) framework development; and, 3) illustrative case study demonstration. During the first phase (foundation and existing knowledge), elements such as Title/Abstract, Aims/Questions, Eligibility Criteria, and Findings of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist were used. The complete PRISMA checklist can be found in study by O'Dea et al. (2021) and the guidance on designing and developing searches can be found in the publication by Siddaway, Wood, and Hedges (2019). These elements of PRISMA were used, because it has been widely cited in other disciplines, and there is evidence of improved reporting quality in research reviews (Page & Moher, 2017). The systematic literature review focused on the methods used in the social sciences to perform qualitative analyses and computational natural language processing algorithms that can perform the social science qualitative analyses in three main steps (see again Figure 2), which could enable the development of the proposed framework.

During the second phase (framework development), process maps grounded on the systematic literature review were generated, as they allowed for the description of the flow of the qualitative methodology in connection with the existing computer science algorithm to develop the proposed framework—see Figure 6. During the third phase (illustrative case study demonstration), the case study included the responses of 337 AEC faculty regarding the online class delivery method during the first year of the covid-19 pandemic. The illustrative case study was used, as it allowed the research team to showcase, describe, and test the framework in tangible construction and engineering research with concrete and meaningful qualitative data.

Resulting Framework

The framework is defined as a structured practical guide or tool to guide users through a replicable process using stages or a step-by-step approach (Chesson, Howa, Lott & Ehleringer, 2016; Kallio, Pietila, Johnson & Kangasniemi, 2016; Kumke, Watschke & Vietor, 2016; Squires, Chilcott, Akehurst, Burr & Kelly, 2016, Nurizzati & Hartono, 2023). Figure 6 shows how the proposed construction framework for qualitative analysis fulfills this definition, as it provides a specific step-by-step approach for construction and engineering researchers to complete replicable and rigorous qualitative research projects. As shown in Figure 6, each of the three steps of the qualitative analysis—Describe, Classify/Coding, and Connect—used in the social sciences was matched with a tangible set of computer science natural language processing algorithms, highlighted in the dark, cyan-colored box, to be used in the construction and engineering disciplines. It is essential to emphasize that the proposed framework is intended to aid researchers in the execution of qualitative research and not to replace judgment and interpretation of the qualitative data beyond the results of the algorithms.

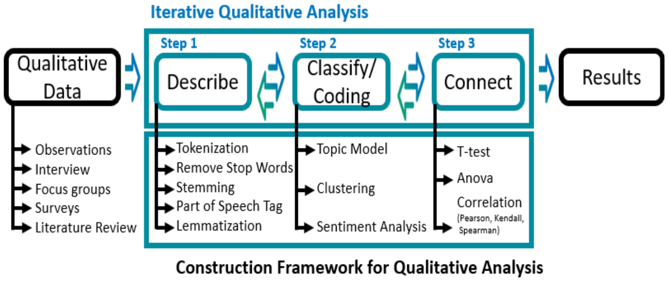


Figure 6. Qualitative analysis methods.

Describe

As explained previously (in the section titled Qualitative Analysis Methods), descriptions are based on the describer's inclinations, perceptions, sensitivities, and sensibilities at any given time (Giorgi, 1992). Therefore, it is very challenging for construction and engineering researchers to replicate. However, the five algorithms presented in this step in the proposed framework seek to give a thorough, straightforward, unbiased, and replicable description of the phenomenological qualitative data, which the construction and engineering researcher's assessments must complement. The five computer science natural language procession algorithms for describing the qualitative data included in the proposed framework are tokenization, removal of stop words, stemming, part-of-speech tag labels, and lemmatization. These can be described as follows.

- Tokenization: This is the activity of breaking a stream or phrase of textual content up into individual symbols, terms, words, or other meaningful elements deemed tokens. Generally, the process of tokenization occurs at the word level and is beneficial as part of the lexical analysis (Vijayarani & Janani, 2016). In this framework, the raw sentences in the text (qualitative data collected by the construction and engineering researchers) are tokenized, which splits the sentence into individual words after which any capitalization and punctuation is removed. Through this step, all the raw sentences are replaced by streams of lowercase words or tokens.

- Remove Stop Words: This is the process of eliminating common words that are not considered relevant to the analysis of the content, because they appear in virtually every text, such as determiners and prepositions. Removal of the stop words is almost universally accepted as a necessary part of content analysis (Riloff, 1995). In this framework, the tokens, from the previous process, considered stop words, are eliminated and not considered for the analysis.

- Stemming: This is the removal of the affixes—both prefixes and suffixes—from a word, leaving only the word's root or stem (Ozturkmenoglu & Alpkocak, 2012). Stemming combines derived word forms to a common stem, allowing for the retrieval of text independently of the specific word form used in the documents (Braschler & Ripplinger, 2003). This process is done with a single word, token, at a time (Ozturkmenoglu & Alpkocak, 2012). Three common stemming algorithms are Snowball, Porter, and Lancaster Stemmers. In this framework, stemming is used to increase the matches among the terms and the data, and improve the quality of those matches.

- Part-of-Speech Tag Labels: Label each word in the text with its particular grammar or syntactic function—adjectives, adverbs, articles/determiners, conjunctions, interjections, nouns, prepositions, pronouns, or verbs. A part-of-speech tag is commonly used as part of linguistic text analysis (Yuan, 2010). In this framework, a part-of-speech tag is used to determine the role of each word and how they relate to one another and help the researcher understand the meaning of statements as a whole.

- Lemmatization: This is the task of finding the dictionary form of a given word or lemma. Lemma is the recognized form of a lexeme, a basic lexical language unit, "consisting of one word or several words, considered an abstract unit, and applied to a family of words related by form or meaning" (Lexeme, 2018). Lexeme refers to the set of all forms of a word with the same meaning, and lemma refers to the particular form chosen as the base form to represent the lexeme. Lemmatization operates on the complete text rather than a single word at a time. Depending on the part-of-speech tag, it can discriminate between words with different meanings (Ozturkmenoglu & Alpkocak, 2012). In this framework, lemmatization is used to determine the word lemma, so different identified forms of a word can be analyzed as the same.

Classify / Coding

This second step allows grouping and assigning labels to the words and sentences that convey similar meanings (Graneheim & Lundman, 2004). The coding process allows construction and engineering researchers to interpret large text segments in new ways or meanings. The meanings are linked to identified themes (Belotto, 2018). The three computer science natural language algorithms to classify/code the textual data included in the proposed framework are:

- Sentiment Analysis: This is a proxy to measure emotion and categorize text according to an idea of what appropriate sentiments are. Analysis datasets are constructed with typical sentiment labels that are manually assigned (Kenyon-Dean, et al., 2018). The analysis goal is to determine the attitude or emotional state held by the author of a text (Kenyon-Dean et al., 2018). In this framework, sentiment analysis is used to evaluate the text automatically, determine the associated sentiment, and classify it as positive, negative, or neutral text.

- Clustering: This separates the different elements of the qualitative data, based on common characteristics. The three most popular algorithms to cluster data are: 1) the Gaussian mixture model; 2) spectral clustering; and, 3) K-means. The K-means algorithm is an iterative clustering algorithm that has several advantages, such as simple mathematical ideas, fast convergence, and easy implementation (Yuan & Yang, 2019; Li, Yu, Hang & Tang, 2017). Therefore, its application in the construction and engineering disciplines is broad. In this framework, the K-means algorithm is used to identify replicable patterns that are generally not easy to identify by construction or engineering researchers.

- Topic Model: This model consists of clustering the text into a specific number of topics/themes, as chosen by the researcher. The most popular machine-learning algorithm to do this is the Latent Dirichlet Allocation (LDA). The LDA represents each block of text as a probability distribution over topics and represents each topic as a probability distribution over words. LDA provides an analysis methods for a large amount of unclassified text data, and serves as an alternative to other classifications (Schwarz, 2018). This framework uses the LDA algorithm to uncover additional hidden themes in the collected text.

Connect

This third step of the framework includes the traditional inferential statistical methods—T-test, ANOVA, correlations, etc.). It was assumed that construction and engineering researchers were familiar with these statistical methods; thus, they were considered outside the scope of this research project. Instead, the authors focused on the replicability and rigor of the qualitative analysis.

Illustrative Case Study Demonstration

Using the resulting framework, the computer science natural language processing algorithms were coded using Jupyter Notebook. Jupyter Notebook is a web-based interactive computing platform supporting multiple programming languages. One of the programming languages supported, Python, was chosen to illustrate the framework, because it is an object-oriented, high-level program language that is relatively easy to learn by construction and engineering researchers, allowing them to rapidly write the framework code to help them in the qualitative analysis. It is important to highlight that this section is intended to demonstrate the proposed framework and not to teach Python coding.

Case Study Overview

As universities transitioned in response to the covid-19 pandemic, two online survey instruments were developed and disseminated among U.S. architecture, engineering, and construction (AEC) educators in the Summer and late Fall of 2020 and early 2021. The instruments had seventy closed and open-ended questions. The open-ended questions within the instrument were intended to elicit content-rich data from respondent faculty. One of the open-ended queries aimed to determine AEC faculty's top three concerns for online education delivery. For responses to this particular query, it was expected that there could be three times the number of respondents with many possible combinations. For this case, the top three concerns from 337 AEC faculty were identified and used as the illustrative case study to demonstrate the implementation of a framework for qualitative analysis of construction and engineering disciplines.

For the 337 respondents to the query, the majority identified themselves as males (71.8%). About 61.7% of the responding AEC faculty identified PhD as the terminal degree, followed closely by 35.3% that identified Master's as the terminal degree. From the perspective of academic rank, 29.4% of the respondents identified themselves as associate professors, 25.8% as professors, and 24.6% as assistant professors. The remaining identified themselves as lecturers, visiting faculty, chair, and adjunct professors. From the perspective of total teaching experience, a majority (40.9%) of the respondents had more than 20 years, followed by 18.4% that had 5-9 years, and 16.6% that had 10-14 years, thereby indicating that the majority of the respondents possessed extensive experience within academia.

Describe

The following are the results of the "Describe" step of this illustrative case study implementing the framework for qualitative analysis.

- Tokenization: The qualitative data collected from the participants were split into their component words using the Python natural language toolkit. Table 1 shows a sample of the original data and the tokenized data. It can be observed that the original qualitative data are in the form of sentences, while the tokenized data represent a list composed of individual words. These individual words become the unit of analysis. Figure 7, for example, shows a frequency distribution graph indicating the occurrence of each word in the case study. In the frequency distribution graph, most of the words at this stage are the commonly occurring stop words that do not provide any insight into the phenomena.

Table 1. Case study tokenization.

I.D.	Original Qualitative Data	Tokenized Qualitative Data
1	nan	[nan]
2	inefficiency in communication	[inefficiency, in, communication]
3	lack of hands-on experience for the students\n…	[lack, of, hands, on, experience, for, the, st…
…	…	…
431	differences in faculty member approach and stu…	[differences, in, faculty, member, approach, a…
432	lazy instructors who do not put in the effort …	[lazy, instructors, who, do, not, put, in, the…
433	nan	[nan]

* nan: Response not provided by participant (blank response)

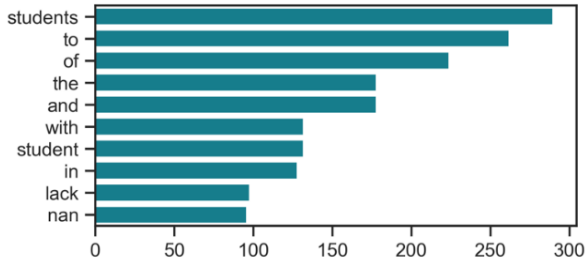


Figure 7. Case study histogram of tokenized data.

- Remove stop words: The stop words were removed from the tokenized data. This was done by comparing each tokenized word to a dictionary of stop words. If the tokenized word was in the dictionary, the word was removed. The researcher can customize this dictionary, should it be needed. Table 2 shows a sample of the tokenized data and the data with the stop words removed (underlined and italicized, respectfully). Figure 8 shows a frequency distribution graph with the occurrence of each word in the case study, not including the stop words. It is worth noting that both the singular and plural forms of student are shown as two different tokens.

- Stemming: The tokenized data with the stop words removed was further processed to produce the morphological variants of the root/base words of all tokens. This was done using one of the stemming algorithms known as Snowball Stemmer. Figure 9 shows the frequency distribution of the stemmed word. It is worth noting that the ranking, based on frequency, of some of the stemmed words parallels the ranking from the non-stemmed words, while the ranking of others have changed. For example, the stemmed “engag” and “learn” rank much higher, perhaps due to the multiple possibilities for responding to written variants of those stemmed words.

Table 2. Case study with stop words removed.

I.D.	Tokenized Qualitative Data	Stop words Removed Qualitative Data
1	[nan]	[]
2	[inefficiency, *in*, communication]	[inefficiency, communication]
3	[lack, *of*, hands, *on*, experience, *for*, *the*, st…	[lack, hands, experience, students, lack, inte…
…	…	…
431	[differences, *in*, faculty, member, approach, a…	[differences, faculty, member, approach, stude…
432	[lazy, instructors, who, *do*, *not*, put, in, the…	[lazy, instructors, put, effort, keep, materia…
433	[nan]	[]

* nan: Response not provided by participant (blank response)

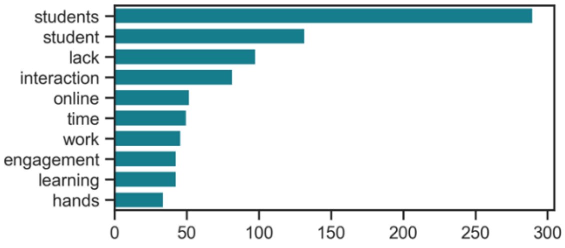


Figure 8. Case study histogram of tokenized data with stop words removed.

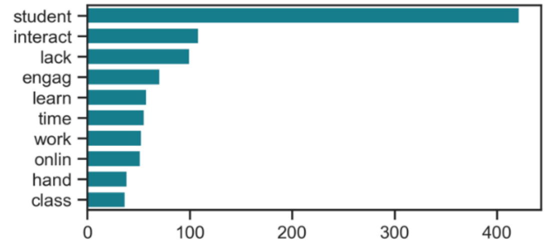
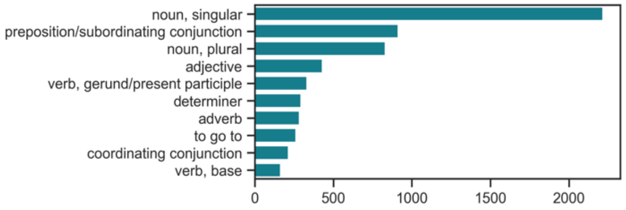
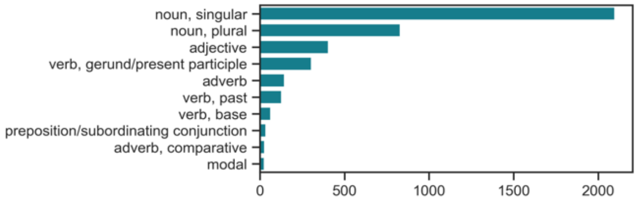


Figure 9. Case study histogram of stemmed data.

- Part-of-speech tag: Each data token was evaluated and classified according to its grammar or syntactic function. This was performed using the Python Natural Language Toolkit, and each word was interpreted and tagged accordingly. Figures 10(a-b) show the frequency distribution of the grammar functions of the data with and without stop words, respectively. It is worth mentioning that, when comparing the frequency of all words, Figure 10(a), and all words with stop words removed, Figure 10(b), the most common grammatical function in the data is nouns. The histogram does not show “determiner” and “coordinating conjunction” with the stop words removed. Also, the “prepositions/subordinating conjunctions” appear in much less quantity in the stop words histogram. Since these words do not provide insight into the phenomena, it is recommended to remove the stop words before doing a part-of-speech analysis. Further analysis can also be performed to determine the most frequent words and their grammatical functions in the data. For example, in this case study, the most common words used were: noun, “students”; adjective, “limited”; verb, “learning”; and, adverb, “less.” This is important in qualitative data analysis, as it provides an additional dimension not apparent in the previous processes and is extremely challenging and time-consuming to be completed manually by construction or engineering researchers.



(a) All words included.



(b) Stop words removed.

Figure 10. Case study—part of speech.

- Lemmatization: The multiple inflection forms of a word were processed in order to group them into a single item. The words used, with different inflection forms, were the tokenized data with the stop words removed. This was done using one of the lemmatization algorithms known as Spacy. Spacy was used because it is a library for advanced Natural Language Processing in Python built on the latest research. Figure 11 shows the frequency distribution of the lemmatized words. It is worth noting that the frequency of lemmatized words is similar to the stemmed words. However, the frequencies are not exactly the same. Given that the lemmatization includes an understanding of the language, the results were considered to be more robust than the result from the stemming process, as it considered the part of speech of each word.

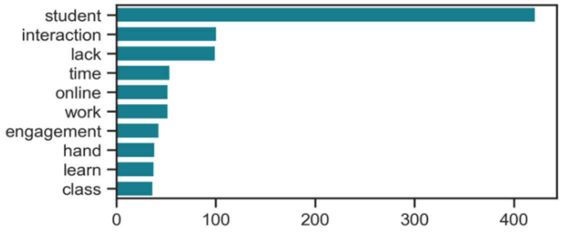


Figure 11. Case study histogram of lemmatized data.

In summary, putting it all together to "describe" the collected information in this case study, based on the proposed framework for qualitative analysis, the participants' number one priority was the students—as revealed by the stop words removed, stemming, lemmatization, and part of speech—followed by interaction—as revealed in stemming, lemmatization, and part of speech. The most common adjective was "limited," and the most common verb was "learning." Thus, qualitative data analysis can be "described," while focusing on students, interaction, limited, and learning. It is important to highlight that the result produced by this framework will be replicable across multiple researchers performing the qualitative analysis—an important element in quality research.

Classify / Coding

Following are the results of the Classify/Coding step of this illustrative case study implementing the framework.

- Sentiment Analysis: Each participant's answer was analyzed and classified as positive, negative, or neutral, according to the emotion represented. This was achieved using a rule-based model for general sentiment analysis named Valence Aware Dictionary and Sentiment Reasoner (VADER). Figure 12 shows the frequency of the participants' answers on sentiment. It can be observed that there was a similar number of answers that conveyed positive and negative emotions. This is important, as this analysis provides the basis to characterize the respondents' sentiments objectively.

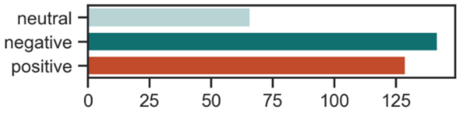
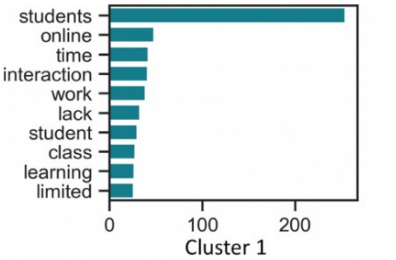


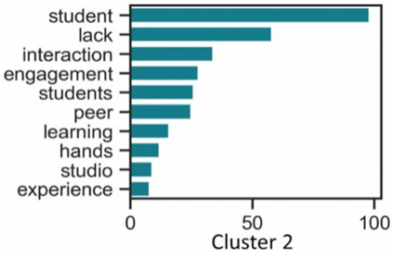
Figure 12. Case study sentiment of analysis.

- Clustering: Unsupervised machine learning algorithms analyzed the unlabeled participants' answers in order to discover hidden patterns or groupings based on similarities in the answers. Unsupervised machine learning was used, due to its ability to discover similarities and differences in the information, making it an ideal analytical approach for qualitative analysis. The first algorithm used was the Term Frequency-Inverse Document Frequency (TF-IDF) to rank the importance or relevance of string representations (words, phrases, lemmas, etc.) in each particular participant's answer among the collection of answers of all participants. After the TF-IDF was used, the K-means algorithm was used. The K-means works by selecting cluster centroids using an empirical probability distribution of any point's contribution to the overall inertia. The K-means algorithm was used to calculate the sum of the square distance of a different number of groups (between 2 and 9). The sum of the square distance decreased as the number of groups increased. However, as the number of groups increased, the differences between groups decreased. Therefore, four clusters were selected to balance the sum of the square distance with the differences among the groups. Figure 13 shows the word frequency for each of the four clusters. It can be seen that cluster 3 is composed only of the answer "none." Although this validation was not performed intentionally, it demonstrates how respondent choices of "none" were totally different from the other clusters' answers, according to this algorithm. To analyze the other three clusters, the top four words, based on occurrence and disregarding students, are summarized in Table 3. This clustering reveals the hidden pattern that some responders focus more on certain aspects, while others in other aspects. Based on the words associated with each cluster, it is apparent that all cluster answers involved interaction, in addition to students. However, analyzing the other words of the cluster, the following partner emerges: Cluster 1 answers emphasize the online, time, and work elements. Cluster 2 answers put more emphasis on lack, engagement, and peer. Cluster 4 answers put more emphasis on face, lack, and time.

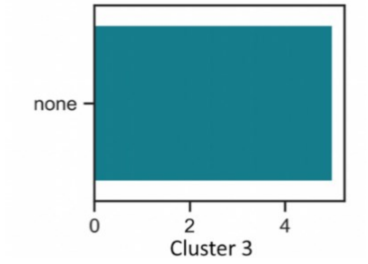
- Topic Model: The Latent Dirichlet Allocation (LDA) was used on the qualitative data to identify the topics. LDA was used because it is a generative probabilistic model that uses a three-level hierarchical Bayesian model, which makes it an ideal model to represent qualitative data explicitly. Four topics were selected to compare the LDA and the K-means algorithm. Figure 14 shows the word frequency for each of the four topics. It can be seen that the LDA model created the four topics—A, B, C, and D. Table 4 summarizes the top four words of each of the four topics. Similar to clustering, patterns emerged from the words associated with each topic. It is apparent that all of the answers to the topics involved interaction, in addition to students. However, when the other words of the topics were analyzed, the following four patterns emerged. Topic A answers put more emphasis on engagement, class, and lack. Topic B answers put more emphasis on online, limited, and lack. Topic C answers put more emphasis on lack, learning, and online. Topic D put more emphasis on lack, face, and work.



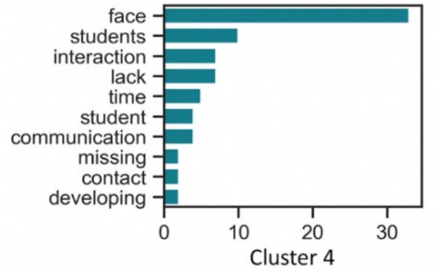
(a) Online, time, and work elements.



(b) Lack, engagement, and peer.



(c) None.

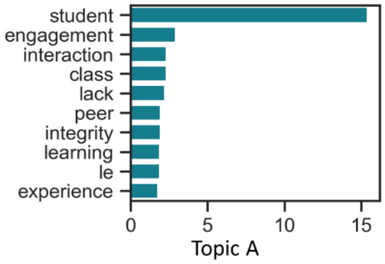


(d) Face, lack, and time.

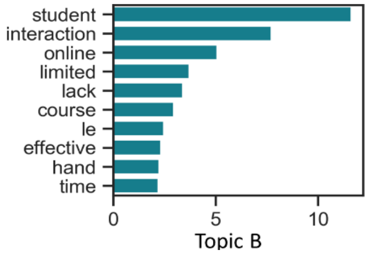
Figure 13. Case study of unsupervised machine learning clustering.

Table 3. Case study relevant clustering.

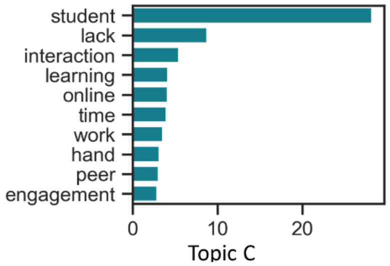
Cluster	Top four words (not including students)
1	Online Time Interaction Work
2	Lack Interaction Engagement Peer
4	Face Interaction Lack Time



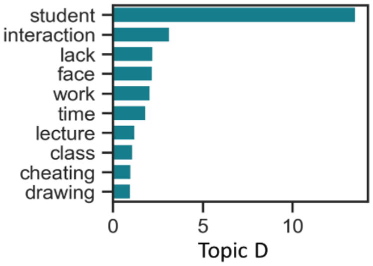
(a) Engagement, class, and lack.



(b) Online, limited, and lack.



(c) Lack, learning, and online.



(d) Lack, face, and work.

Figure 14. Case study latent dirichlet allocation (LDA) topic model.

Table 4. Case study relevant topic model.

Topic	Top four words (not including students)
A	Engagement Interaction Class Lack
B	Interaction Online Limited Lack
C	Lack Interaction Learning Online
D	Interaction Lack Face Work

In summary, putting it all together to "classify" the collected information in this case study, based on the proposed framework for qualitative analysis, the participants' sentiment was mixed, as there were approximately the same amount of responses expressing positive and negative emotions, though some had a neutral emotion. The clustering and topic algorithm also revealed that both "student" and "interaction" were the most important to the participants, as they can be found in all clusters and topics, followed closely by "lack," which was found in all but one cluster. Table 5 shows that the main differences between the three clusters and the four topics were the other elements of relevance for the participants.

Table 5. Case study relevant topic model.

Words\Groups	1	2	4	A	B	C	D	Count
Interaction	✓	✓	✓	✓	✓	✓	✓	7
Lack		✓	✓	✓	✓	✓	✓	6
Engagement		✓		✓			✓	3
Face			✓				✓	2
Class				✓				1
Online					✓	✓		2
Peer	✓	✓						2
Time	✓		✓					2
Learning						✓		1
Limited					✓			1
Work	✓							1

Conclusions

In this paper, the authors addressed the challenge that construction and engineering researchers have faced regarding resource (time) intensiveness, replicability, and rigor, when performing qualitative analyses, by describing a qualitative analysis framework grounded on the social sciences knowledge of qualitative analysis and computer science natural language processing algorithms. The framework was developed following a mixed research method design divided into three phases: 1) foundation and existing knowledge; 2) framework development; and, 3) illustrative case study demonstration. A literature review was conducted on the methods used in the social sciences to perform qualitative analyses and computational natural language processing algorithms that can perform the qualitative analysis in the main three steps (see again Figure 2) in order to develop the proposed framework. The literature review demonstrated that qualitative analyses in social sciences literature are rich and fragmented. Thus, the section in this paper titled Qualitative Analysis Methods serves as a synthesis and guide for construction and engineering researchers to conduct systematic qualitative analysis research. Based on the literature, the qualitative analysis has three main steps: Describe, Classify/Coding, and Connect. During the second phase, grounded on the systematic literature review, process maps were generated describing the flow of the qualitative methodology in connection with the existing computer science natural language processing algorithm to develop the proposed framework (see again Figure 6). For each one of the steps in the qualitative analysis, the framework included algorithms with supporting evidence to be used in construction and engineering research. Thus, the section on Resulting Framework provides all the necessary elements for construction and engineering researchers to perform replicability and rigorous qualitative analyses.

Lastly, a case study described the framework for the construction and engineering discipline with concrete and meaningful qualitative data. The illustrative case study included the responses of 337 AEC faculty within the U.S. regarding the online class delivery method during the first year of covid-19. The results of the qualitative analysis using the framework revealed that the highest priority of the faculty were "students" and "interaction," and the number one syntactical words were the "students" (noun), "limited" (adjective), and "learning" (verb). Thus, the analysis of the qualitative data "describe" it as focusing on students, interaction, limited, and learning. Furthermore, the faculty answers indicate that all possible grouping included "students" and "interaction."

It is essential to highlight that the result produced by the proposed framework be unbiased and replicable, the use of this framework be grounded on theoretical knowledge from the social and computer sciences in order to provide the basis for rigorous analysis, and that it take less time and resources than the conventional method. One of the limitations of the finding is that the researchers must be versed in computer programming methods to achieve the desired results. To the authors' knowledge, this is the first paper that attempts to create a framework for the construction and engineering disciplines by bridging the gap between the social sciences and computer science. Thus, the resulting framework contributes to the body of knowledge through the scholarship of integration by synthesizing the knowledge across two disciplines (social sciences and computer science) to provide the construction and engineering disciplines with an unbiased, rigorous, and replicable qualitative analysis approach that can be implemented by researchers using their content-rich textual datasets to benefit society with their new findings.

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Biographies

TULIO SULBARAN is a full professor of construction management at the University of Texas at San Antonio. He earned his BS degree in civil engineering from the Universidad Rafael Urdaneta in 1993, Master of Science in Civil Engineering from the Georgia Institute of Technology in 1998), and PhD in Civil Engineering with a concentration in construction management and a minor in computer engineering from the Georgia Institute of Technology in 2022. His research interests include construction management, data analytics, decision-making, artificial intelligence, and work-force development. Dr. Sulbaran may be reached at Tulio.Sulbaran@utsa.edu

SANDEEP LANGAR is an Assistant Professor of Construction Management at the University of Texas at San Antonio. He earned his B.Arch. degree from the University of Mumbai, India, MS in Building Construction Science and Management in 2012, and PhD in Environmental Design and Planning in 2013 from Virginia Tech. His research interests include construction education, building information modeling (BIM), sustainable and resilient strategies and technologies adoption, and enhancing the resilience of built facilities against natural hazards. Dr. Langar can be reached at sandeep.langar@utsa.edu

SANJEEV ADHIKARI is a Graduate Program Coordinator and Assistant Professor of Construction Management at Kennesaw State University. He earned his PhD in Civil Engineering, focusing on construction management, from Michigan Technological University in 2008. He has been involved in numerous professional societies to supplement his teaching and research, including ASCE, ACI, ASEE, ASC, ATMAE, and TRB. His research output has been well disseminated, as he has published eighty-plus peer-reviewed journal papers and conference proceedings. His research interests include creating innovative sustainable materials, digital construction, bim and vdc, virtual testing lab, construction education, and sustainability. Dr. Adhikari may be reached at sadhika3@kennesaw.edu

RACHEL MOSIER is an Associate Professor of Construction Engineering Technology at Oklahoma State University. She earned her BS in Architectural Engineering degree from Oklahoma State University in 2001, MS in Construction Administration from the University of Oklahoma in 2009, and an interdisciplinary PhD in Engineering from the University of Oklahoma in 2013. Her interests include engineering education, resilience, and the cost of sustainable construction. Dr. Mosier may be reached at rachel.mosier@okstate.edu

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College of Engineering and Computer Science
Room: JD 4510
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Office: (818) 677-5003
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Editor-in-Chief
Office: (818) 677-5003
Email: editor@ijme.us
Department of Manufacturing Systems Engineering & Management
California State University-Northridge
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Northridge, CA 91330